ANNUAL CHANGES IN SPATIAL AGGREGATION OF ATLANTIC COD, *Gadus morhua* AGE CLASSES IN NAFO DIVISIONS 2J3KL AND 4RS (1978–1994)

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Annual Changes in Spatial Aggregation of Atlantic cod, *Gadus morhua* age classes in NAFO Divisions 2J3KL and 4RS (1978-1994)

by

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Abstract

Geographic contraction of range can be explained by using a basin model (MacCall 1990) which predicts that density-dependent populations will tend to contract toward the most favorable habitat as the population collapses. Literature has suggested that the distribution of demersal species such as Atlantic cod, *Gadus morhua* (Swain 1993) may be a product of the basin model phenomena. In this thesis I examine change in Atlantic cod aggregation during stock decline as it depends on age class, in order to better understand the spatial dynamics of the collapse of the Atlantic cod stocks in both NAFO (Northwest Atlantic Fisheries Organization) divisions 2J3KL (northeast Newfoundland Shelf) and 4RS (Northern Gulf of St. Lawrence), and explore how the basin model and density-dependent habitat selection relate to the change in aggregation into restricted areas during the collapse of Atlantic cod.

I use research vessel data which was collected by Department of Fisheries and Oceans (1978-1994) in NAFO divisions 2J3KL, and 4RS to identify common characteristics of the spatial dynamics of the cod collapse. I explore the distributional shifts and change in aggregation of Atlantic cod age classes ($\leq$2-12+ yrs) and age groups (ages $\leq$2, ages 3-4 ages, 5-6 and age 7-12+) from 1978 to 1994, by using distributional maps, the Gini index, the variance, the skewness of the frequency distribution, the exponent of power law, and the shape of cumulative frequency distribution.

My results show that the most distinct measure of aggregation was the Gini index in combination with the distribution maps. These measures show that older cod peaked in aggregation while collapsing into fewer locations in the early 1990s and that the cod

distribution collapse into reduced areas was specific to older age classes of Atlantic cod, with a lesser degree of spatial contraction in younger age classes and little or no contraction in the youngest age classes and variable rather than fixed locations of aggregation. Thus I offer an alternate explanation for the collapse into restricted areas, one that does not depend on habitat selection, as in the basin model. The alternative explanation is that each year reproductively mature cod aggregate to spawn and that as the population shrinks the number of spawning locations shrinks but not necessarily at the same site each year. Patterns of aggregation in this study have important implications for these stocks and that aggregative behavior by age group should be monitored and displayed for all cod stocks.

Spatial structure and degree of aggregation should be monitored and displayed for all demersal species, not just for management of pelagic species. In this instance, when evaluating cod aggregation during a collapse a measure of aggregation that performs well, the Gini index should be considered in science advice to management.

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Chapter 1: Introduction and Literature Review

1.1 Introduction

Density-dependent habitat selection has been explored in several ecological and biological studies of habitat use. Specifically, density-dependent habitat selection refers to how the choice of habitat depends upon population size and local density therefore affecting the relative distribution of a population among habitats (MacCall 1990). One of the common phenomena associated with density-dependent habitat selection is expansion or contraction of population range in response to changes in abundance. This phenomenon has been observed in a wide range of species from large mammals (Allen 1972) to birds (Lenington 1980) and insects (Whitham 1980). It has also been studied in aquatic systems and extended to the dynamics and geographic behavior of entire fish populations. MacCall (1990) invoked density-dependent habitat selection to explain large-scale patterns of habitat usage by marine fish. This study, among others (Myers and Stokes 1989), led to the adoption of density-dependent habitat selection as an important mechanism in marine fish spatial ecology (Shephard and Litvak, 2004).

Density-dependent habitat selection has been used to explain range contraction in relation to several fish stock collapses. Geographic contraction of range has, for some time now, been considered characteristic of pelagic species such as the Pacific sardine, *Sardinops sagax*, and Peruvian anchovy *Engraulis ringens*. In the case of the Pacific sardine fishery, when the population fell below 10,000 tons in the 1960s and 1970s (MacCall 1979) most of the remnant sardine population consisted of a few large schools

occupying consistent locations in or near southern California's larger estuaries such as San Diego Bay (MacCall, 1990). More recent research has suggested that the distribution of demersal species such as Atlantic cod *Gadus morhua* (Swain 1993) during its collapse may also be a product of density-dependent habitat selection.

In this thesis I examine change in Atlantic cod aggregation during stock decline as it depends on age class, in order to better understand the spatial dynamics of the collapse of cod stocks. I compare findings on cod in NAFO divisions 2J3KL with those related to cod in NAFO divisions 4RS (refer to Figure 1.1) in order to identify common characteristics of the spatial dynamics of the cod collapse. The data for this work were obtained from the stratified random trawl surveys (1978-1994) conducted by the Department of Fisheries and Oceans. I explore the distributional shifts and geographic contraction of age classes (<2-12+) by using distributional maps, the Gini index, the variance, a measure of skewness, the exponent of power laws, and the shape of cumulative frequency distribution to summarize change in aggregation by year and age class. In addition I look at whether MacCall's basin model and density-dependent habitat selection are consistent with the change in aggregation into restricted (fewer) areas during the collapse of Atlantic cod.

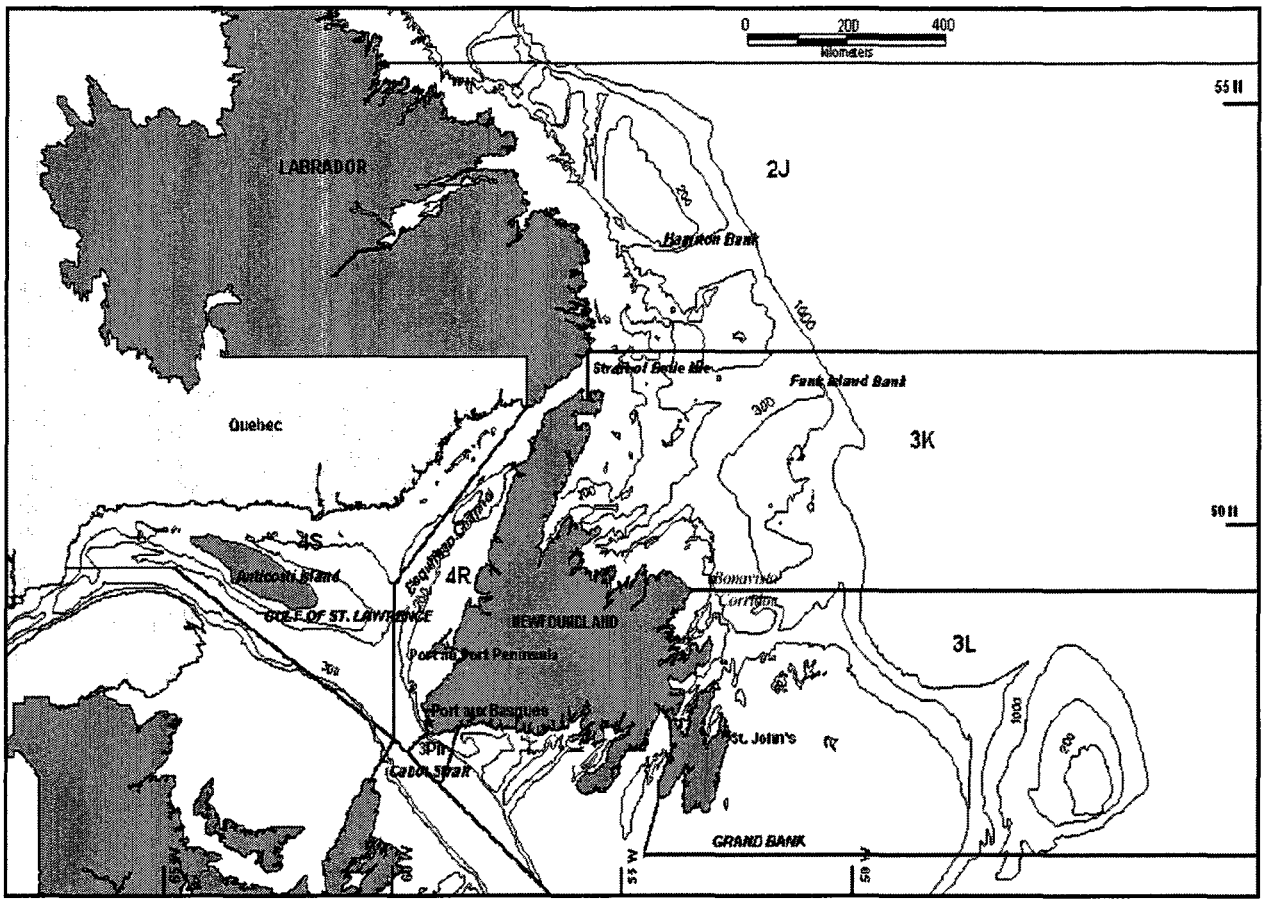

Figure 1.1. Map of the study area, North Atlantic Fisheries Management Divisions 2J3KL and 4RS.

1.2 Geographic Range Contraction and Abundance

Geographic contraction of range can be explained by using a basin model (MacCall 1990) to describe how the localized density changes with respect to total population abundance (Shephard and Litvak 2004). The basin model predicts that density-dependent populations will tend to contract toward the most favorable habitat as they are fished down (MacCall 1990, Hilborn and Walters 1992). A corollary of range contraction is the observation that catch per unit effort (CPUE) will not decline as fast as the total abundance, which is the volume of the 'liquid' in the basin (MacCall 1990). In the case of the Northwest Atlantic cod as cod abundance decreased, local cod densities increased helping to sustain high CPUE despite declining abundance (Rose and Kulka 1999).

Geographic contraction of range, also known as a concentration or aggregation, has been measured using several different indices including indices in geostatistics (Mello and Rose 2005); economic measures of distribution including the Gini index (Myers and Cadigan 1995), which is defined by the Lorenz curve (Dagum 1985) along with quantile plots (Laurel *et al.* 2004), power law exponents (Perry 1981) and spatial variance indices (Horne and Schneider 1997). Mello and Rose (2005) used geostatistical methods to quantify fish aggregation patterns over a range of scales (100 m to 67 km) using both simulated and acoustic density data on Atlantic cod (*Gadus morhua*) to examine how changes in aggregation patterns influenced the precision of geostatistical density indices. They concluded that geostatistical modeling is an effective way to describe and quantify

the spatial variance of fish at different scales of observation permitting comparisons of spatiotemporal changes in density distribution and estimations of the precision of density indices while accounting for the effects of heterogeneous distributions, outliers and the typically large number of zero and low density observations. Mello and Rose (2005) did not examine annual change in aggregation in Atlantic cod.

Smedbol *et al.* (2002) reviewed the structure, abundance and distribution of 10 cod stocks in Atlantic Canada using the available time series of abundance. Three indices were calculated: the area of occupancy, the minimum area occupied by 95% of the stock, and the Gini index of aggregation. From these calculations Smedbol *et al.* (2002) concluded that no trend in geographic range was evident but that most stocks that underwent a large decline in abundance demonstrated an increase in the degree of aggregation.

Zwanenburg *et al.* (2002) examined measures of concentration, prevalence and local density for seven marine species commonly caught during annual groundfish trawl surveys conducted by the Department of Fisheries and Oceans. They also examined the relationship between these distributional indices and estimates of overall species abundance. The proportion of the total survey area occupied by the top nth percent of the total annual population estimate defined the concentration. "Prevalence was defined as the proportion of the total number of standardized trawl hauls (sets) completed in year *i* containing >0 individuals of the species of interest and indicates how widely the species is distributed in the survey area with reference to density" (Zwanenburg *et al.* 2002, Pg.2). They concluded that these measures should not be interpreted individually; instead

they recommended that a combination of the measures be analyzed to provide various indicators of overall species abundance.

Myers and Cadigan (1995) constructed a statistical model to test whether traditional catch at age data derived from research surveys (1978-1994), led scientists to conclude that the collapse of the northern cod stocks was caused by an increase in natural mortality in the first half of 1991. In that model they assumed that research survey estimation errors of abundance by age and year were independent. They constructed a population and statistical model, which included the calculation of the degree of concentration (aggregation) using Lorenz curves and in turn calculating the Gini index. They found that the concentration of cod increased over time as displayed by the Lorenz curves and Gini index. In addition the increase in concentration (aggregation) occurred during the late 1980s and early 1990s, leading up to the cod collapse (Myers and Cadigan, 1995). This is consistent with the results of Smedbol *et al.* (2002) who also found an increase in aggregation in cod stocks that underwent a large decline in abundance (Smedbol *et al.* 2002).

Petitgas (1998) described how spatial distribution changes as population abundance varies. He used four models for biomass-dependent spatial dynamics and characterized these using geostatistical aggregation curves. Data from two spatio-temporal series of monitoring surveys were analyzed: a groundfish bottom trawl survey and a pelagic echointegration survey. The geostatistical aggregation curves that Petitgas used are similar to the Lorenz curves used by Myers and Cadigan (1995). Petitgas concluded that both demersal and pelagic fish showed similar spatial dynamics for medium and high abundances.

Schneider *et al.* (1997) examined range contraction using catches of small cod in three length groups corresponding to ages 0+, 1+ and 2+ using data from 1959-1964 and 1992-1994 at a series of coastal sites extending over 1500 km of coastline. They concluded that in years of low cohort size, contraction did not occur relative to geographically fixed foci or annually shifting foci in any of the three length groups. Overall they found that in the absence of range contraction, the size of newly settled cohorts of cod, at the scale of the coastline, can be estimated from changes in local density (catch per unit effort).

At a smaller scale Laurel *et al.*(2004) measured how fish density, movement and aggregative behaviour (i.e. shoaling or schooling) changed with habitat in Atlantic cod *Gadus morhua* and Greenland cod *Gadus ogac*, using a combination of field -seines, mark-recapture and laboratory experiments. They examined the juvenile cod densities from seine catches using quantile-quantile plots (Lorenz curves) of percent abundance versus percent area to determine the degree of aggregation of fish in the field. Within-site catch variation indicated both species aggregated more in sand than eelgrass habitat and that Atlantic cod aggregations over sand increased as density in eelgrass increased. They concluded that juvenile cod modify their behavior with changing density, and that juvenile cod aggregate more over unstructured habitat (i.e. unvegetated sand) compared to over structured habitats (i.e. eelgrass). Aggregation also increased over sand sites in years when abundance in eelgrass habitats was high, indicating this behaviour is density-dependent (Laurel *et al.* 2004).

There are several reasons for the divergent findings on the relationship between range contraction and abundance within the literature, including differences in the species

studied, the methods used, and the research questions asked. Zwanenburg *et al.* (2002) and Smedbol *et al.* (2002) both included several marine species in their analyses and found that several measures could be used in concert to measure aggregation or contraction of range in relation to change in stock abundance. Mello and Rose (2005) and Myers and Cadigan (1995) focused on the change in aggregation of Atlantic cod, however Myers and Cadigan (1995) used the Lorenz curve (Gini index) while Mello and Rose (2005) used geostatistical methods to quantify aggregation patterns. Both found their measures were effective in measuring aggregation. Petitgas (1998) and Mello and Rose (2005) both used geostatistical methods. However, Petitgas used both pelagic and demersal species in his analyses but nonetheless found the geostatistical method to be an effective measure. Both Schneider *et al.* (1997) and Laurel *et al.* (2004) investigated juvenile cod, but at different spatial scales. Schneider *et al.* (1997) studied the contraction in range of juvenile cod along the coast of Newfoundland at several locations, and Laurel *et al.* (2004) focused their analyses at a far smaller scale, and examined how juvenile cod modified their aggregative behavior as a result of density change in sand compared to eelgrass habitats.

1.3 Distribution Shifts and Range Contraction

Myers and Cadigan (1995), Smedbol *et al.* (2002), Mello and Rose (2005) described the contraction and concentration of range in relation to stock size, while Laurel *et al.* (2004) considered small scale change in aggregation in relation to density dependence of selective habitat and their associated quantitative measures. Several studies investigate the relation between range contraction and change in thermal habitat.

Cod distribution shifts and range contraction have been examined at several spatial scales and over time in divisions 2J3KL and 4RS. Hutchings (1996) used research survey data to examine the density composition of northern cod in Divisions 2J3KL from 1981 to 1992. In order to explore and describe the numerical changes in cod density and the temporal changes in the spatial structure of cod, Hutchings (1996) constructed a density composition model and a nested aggregation model. He concluded that these research vessel survey data indicated a gradual decline in medium density tows (100-500 kg cod tow^{-1}) from 22% in 1982 to 5% in 1991 concomitant with a gradual increase in low density tows (0-100 kg tow^{-1}) from 76% to 93%. However, high density tows (> 500 kg tow^{-1}) remained proportionately constant at roughly 1 to 2% until 1992, when the density of the tows rapidly declined, some being diminished to zero. Hutching's (1996) models demonstrated how contraction in range could cause overestimation of abundance in a random stratified survey. Hutchings (1996) also explored other hypotheses for the collapse of the northern cod fishery, including a southerly shift in cod distribution that had occurred in 1984, 1985 and 1988 onward and that was thought to have been linked to changes in water temperatures and prey abundance (Rose *et al.* 1994). Another theory proposes that the increase in aggregation through the late 1980s possibly increased the vulnerability of northern cod to commercial fishing and contributed to the rapid cod stock decline (Hutchings, 1996).

Atkinson *et al.* (1997) examined the spatial shift of northern cod toward the center of their distribution in 2J3KL using data from the annual fall bottom trawl surveys done between 1981 and 1993. They hypothesized that southerly distribution changes later in the period would be accompanied by shrinkage in the range occupied by the stock and

that occupied range would be positively correlated with stock abundance. The data analysis demonstrated that the area cod inhabited from the northern Grand Banks to Labrador (NAFO divisions 2J3KL) was positively correlated with stock abundance. Hence the stock decline that occurred during the late 1980s and early 1990s was accompanied by a shrinkage in occupied range. The result of Atkinson *et al.* (1997) was based on the statistical ellipse technique, which was used to describe the central tendencies of the research survey catch data and the area encompassing 90% of the stock biomass as calculated from the same data. They concluded that the distributional changes led directly to an increased vulnerability to the offshore and inshore fisheries, which were concentrated in the southern area, thereby contributing to the rapid decline in stock abundance (Atkinson *et al.* 1997). Swain *et al.* (1998) compared habitat associations of southern Gulf of St. Lawrence Atlantic cod and American plaice (*Hippoglossoides platessoides*) between the summer feeding season on the Magdalen Shallows and the over wintering period in the Cabot Strait. Swain *et al.* (1998) used data from bottom trawl surveys which were conducted in September 1993, 1994, and 1995 and January 1994, 1995 and 1996. Both species occupied much deeper, warmer water in winter than in summer. Swain *et al.* used Lorenz curves to compare the degree of aggregation of American plaice in September and January. To identify the habitat variability bivariate cumulative distribution function (CDF) were calculated to identify the habitat variable (depth or temperature) that was most strongly associated with fish distribution.

Rose and Kulka (1999) examined patterns of aggregation and cross-shelf migration in the Bonavista corridor by using acoustic and trawl survey data and observer records from the offshore fishery to examine changes in spatial distribution patterns of the

northern cod from 1983 to 1993 and their relationship to CPUE (catch per unit effort) from the offshore fishery. They tested for hyperstability of CPUE relative to biomass at several scale changes in relation to local density and aggregation where hyperstability is defined as local densities increasing with decreasing biomass (Hilborn and Walters, 1992). Rose and Kulka (1999) hypothesized that changes in spatial patterns of abundance of demersal fish can bring about changes in CPUE and catchability (ratio of CPUE to abundance). They concluded that as a southerly shift in distribution was occurring, local densities of the extant aggregations were being maintained or even increasing. Therefore, although stocks were actually declining in abundance, the tendency of cod to hyperaggregate led scientists, industry leaders and managers to believe that the stock was healthy. Furthermore, contemporary fishing practices allowed exploitation of these vulnerable dense aggregations and severe overfishing to occur (Rose and Kulka, 1999).

Castonguay *et al.* (1999) and Rose and Kulka (1999) both examined the apparent southward shift in the distribution of the Atlantic cod in the 1990s. Castonguay *et al.* (1999) concluded that there was a southward shift in the Gulf of St. Lawrence, along with a shift to 200 meters and deeper. Shifts in cod distribution patterns in the period before and after closure of the northern Gulf cod fishery in 1992-1993 were also examined by Castonguay *et al.* (1999) using research vessel survey data from 1978 to 1994. They examined changes in the distribution of individual age classes of Atlantic cod. Changes in cod distributions with respect to depth, temperature, and latitude in both winter (1978-1994) and summer (1984-1995) were determined in relation to a water cooling event that occurred in the cold intermediate layer (CIL) in the Gulf of St. Lawrence, starting in the mid 1980s. They used a cumulative distribution function method that compares seasonal

distributions of fish with sampled variables (depth, temperature, and latitude). Castonguay *et al.* (1999) concluded that starting in the mid-1980s, the distribution of northern Gulf cod was more southerly and deeper in winter than in the past and that the latitudinal shift co-occurred with the cooling of the northern Gulf at mid-depth. The authors suggested that cod responded to a change in their habitat by altering their migration and distribution patterns.

1.4 Age specific geographic contraction

Many papers have looked at whether the distribution of fish varies with age (Wigley and Serchuk 1992, Dalley and Anderson 1997, Swain 1999). Very few studies have looked at changes in aggregation of the entire stock over time (Myers and Cadigan 1995, Smedbol *et al.* 2002), and even fewer (Swain 1993, Swain and Wade 1993) have looked at whether the change in aggregation over time depends on age. Myers and Cadigan (1995) found that cod aggregated in the early 1990s during the collapse (Myers and Cadigan 1995), but Schneider *et al.* (1997) found that this did not apply to juveniles.

Swain (1993) examined annual variation in the bathymetric pattern in Atlantic cod in the southern Gulf of St. Lawrence from 1971-1991. In addition, he explored age specific relationships between cod density and depth difference between periods of low and high abundance. He concluded that younger fish (age 3-5) at high abundance were found in high densities in shallow water. In contrast the older fish (age 6-8+) at high abundance were found at high densities in deeper water (Swain 1993).

Swain (1999) examined density-dependent redistribution of Atlantic cod in response to temperature change in the southern Gulf. The purpose of his study was to test competing hypotheses related to whether shifts in the distribution of Atlantic cod (*Gadus*

morhua) in the southern Gulf of St. Lawrence are responses to cod abundance or environmental change. Swain (1999) concluded that cod distribution was affected by cod abundance for cod ages 4-8+ years, and age 3+, however there was no effect from environmental conditions except for age 3. Swain and Sinclair (1994) also examined Atlantic cod density dependence and distribution in the southern Gulf for different age classes. They found the area of highest cod concentration (aggregation) expanded significantly as population size increased for young (age 3) cod but not for older cod. Atlantic cod age groups in the southern Gulf of St. Lawrence were also examined by Swain and Wade (1993) who tested the effects of population size on the geographic distribution of age groups 3-8+ over the period 1971-1990. They concluded that distribution was density dependent for all six ages. This study demonstrated that the area occupied by cod in the southern Gulf of St. Lawrence increased as cod abundance increased. The geographic pattern of density distribution at low population sizes suggests that the optimum habitat for cod of all ages (3-8+) tends to be concentrated in western regions of the southern Gulf (Swain and Wade 1993).

Wigley and Serchuk (1992) analyzed commercial landings of Atlantic cod in the Georges Bank- Southern New England region from 1982-1986 to identify spatial and temporal patterns as well as possible distribution shifts. This analysis indicated that cod ages 1-2, age 3, and age 4+ were distributed at different depths during the spring. However, during the autumn, age 3 fish co-occurred with age 1-2 fish, while age 2 cod formed aggregations in deeper water (Wigley and Serchuck 1992).

Kulka *et al.* (1995) described the spatial structure and behavior of schools of adult Atlantic cod prior to and during the sudden downturn in biomass using fishery observer

data and otter trawl data. Specifically they examined the relative amounts of biomass at three locations where the pre-spawning and spawning cod tended to aggregate over the period 1980-1992. They looked at distributional shifts by depth and investigated along shelf movements of schools at a weekly time scale just prior to and during the biomass decline of 1989-1992. Kulka *et al.* (1995) found that during the reproductive period for the Atlantic cod, there were significant changes in distribution and behavior, well before the stock showed signs of collapse. This was evident from the disappearance of fish from the north with time; movements of prespawning/spawning schools becoming more limited; and from indications that the cod extended over a wider range of depths down to 1100 meters (Kulka *et al.* 1995).

Area occupied and abundance are positively correlated for a number of pelagic (Winters and Wheeler 1985) and demersal fish populations (Zwanenburg *et al.* 2002). Generally these studies have shown that changes in area occupancy, over a range of population abundance levels, are the result of correlations between fish density and geographic area occupied. The collapse of the Atlantic cod fishery was clearly associated with spatial and temporal changes in biomass and density of the populations (Hutchings 1996). Until the early 1990s Atlantic cod were considered to be a demersal species for which catch per unit effort could be used to track stock size. However, because adult cod aggregate to spawn and to overwinter their behavior may prove to be closer to that of pelagic species (Kulka *et al.*1995), for which catch per unit effort does not track stock size. Juvenile cod aggregate at smaller scales for protection in shoals (Laurel *et al.* 2004) but there is no evidence that juvenile cod contract into restricted areas with either fixed or moving foci at the large scale of a stock (Schneider *et al.* 1997).

In this thesis I explore the change in aggregation of age classes (<2-12+) from 1978 to 1994 in NAFO divisions 2J3KL and 4RS by using distributional maps, the Gini index, the variance, the skewness of frequency distribution, the exponent of power laws, and the shape of cumulative frequency distribution to summarize change in aggregation by year and age class. In addition I look at whether MacCall's basin model and density-dependent habitat selection are consistent with the change in aggregation into restricted (fewer) areas during the collapse of Atlantic cod. In Chapter 2, the setting will include the interpretation of the physical descriptions of NAFO divisions 2J3KL and 4RS including Atlantic cod fisheries and their histories, along with Atlantic cod distribution, and biology. In Chapter 3, I will describe the methods that were used to calculate several indices to measure change in aggregation of Atlantic cod age classes. In Chapter 4 I will display the results of these measures including a narrative of Atlantic cod age classes distribution maps for divisions 2J3KL and 4RS. Chapter 5 begins with a discussion of the results found from both 2J3KL and 4RS Atlantic cod stocks, explores the change in aggregation over time for each age group, and then moves to a comparison of results between the two study areas. Finally in this Chapter 5 I will draw conclusions based on the results, and compare the results of this thesis to similar research.

Chapter 2: Setting

2.1 Northern Cod Fishery

In the early 1990s a dramatic cod collapse in Newfoundland and Labrador waters led to the implementation of several cod moratoria. These moratoria were implemented in 1992 and 1994, in 2J3KL and 4RS (Figure 1.1) respectively. The cod fishery closures caused profound social, cultural, economic and ecological changes throughout Eastern Canada (Hutchings and Myers 1994).

2.1.1 Divisions 2J3KL (southern Labrador and eastern Newfoundland)

Atlantic cod have been fished in Newfoundland and Labrador waters since the late fifteenth century (citation). The fishery began as a hook and line fishery with traps becoming common in the 1860s and 1870s. Harvesting methods became more advanced in the early 1900s when steam power, large bottom trawls and nylon gill nets were introduced. Technological advances were even more profound in the period after World War II with the arrival of the distant water fleets and nylon gill nets (Hutchings and Myers 1994 and Neis *et al.* 1999).

In divisions 2J3KL (southern Labrador and eastern Newfoundland) northern cod landings ranged from 100 000 t to 150 000 t in the early 1800s and increased to over 200 000 t in the late nineteenth century. From 1900 to 1960 the catch was over 250 000 t per annum. When the factory freezer stern otter trawlers from Europe and elsewhere arrived in the 1950s catches rose dramatically, reaching an all time maximum of 810 000 t in

1968 (Hutchings and Myers 1994). In 1977, the extension of the 200-mile limit dramatically reduced the distant water fishing by non-Canadian fleets in the 2J3KL areas.

From 1978-1988, the first years of Canadian management, commercial landings of cod increased from 140 000 to 270 000 t. In 1991, landings dramatically declined to 64% less than those in 1988. The following year, the number of cod had decreased to almost 3 billion fewer than the number of harvestable cod in the 1960s (Baird *et al.* 1991), which led the Canadian government to impose the northern cod moratorium in July 1992.

2.1.2 Divisions 4RS (northern Gulf of St. Lawrence)

In the 16th century the French regularly fished in the Gulf of St. Lawrence and adjacent areas. Prior to the 1950s and 1960s the cod landings in the Gulf of St. Lawrence were reported based on port of landing instead of area fished. Therefore the landings statistics for Gulf cod are more reliable from the1960s onward (Chouinard and Fréchet 1994).

In the early 1960s, cod landings in the northern Gulf of St. Lawrence reached up to 100 000 t, then stayed around 80,000 t per year, until they reached 105,000 t in 1970 and then declined in 1975 to 60,000 t (Chouinard and Fréchet 1994). Between 1982 and 1984 cod landings increased again and peaked at over 100,000 t, before dramatically declining again to historically low levels of 30,000 t in 1991-1992 (Chouinard and Fréchet 1994, Ouellet *et al.* 1997). The cod moratorium in the northern Gulf was announced in 1994 and lasted until 1997 when a limited fishery was introduced with restricted total allowable catches of up to 6,000t (DFO 2002).

Until 1977, approximately half of the Northern Gulf cod landings were made by non-Canadian fleets. The fixed and mobile gear sectors included vessels fishing long lines, gillnets, and otter trawls. From 1984-1994, landings from the fixed gear sector decreased from 50,000 t to 9,000 t. Over 80% of these landings were accounted for by long lines and gillnets. In the mobile gear sector the reduction in landings and TACs was not as drastic and decreased from 62,000t in 1984 to 20,000t in 1992 (Fréchet and Gagnon 1993, Chouinard and Fréchet 1994).

2.2 Physical Description of the Study Areas

2.2.1 Divisions 2J3KL

Divisions 2J3KL include the southern Labrador Shelf, which levels off at 200m, the northeast Newfoundland Shelf, the northern Grand Bank, and the continental slope to a maximum depth of 1000 m (Figure 1.1). There are several banks within 2J3KL, including the Hamilton Bank off the southern coast of Labrador Shelf which plateaus at less than 200 m deep, along with Funk Island Bank and Belle Isle Bank on the Northeast Newfoundland Shelf which are shallower than 200m. In the southern part of 3L, the Grand Bank covers an extensive area between 100 and 200 m. The nose of the Grand Bank lies within the southern part of 3L. There are also channels with depths greater than 400 m that separate these banks (ICES 2005).

The Labrador Current flows along the shelf southeastward, and maintains low temperatures below 0°C. Ice cover caused by ice flow from the Arctic is often found as far south as the northern Grand Bank (ICES 2005).

The water temperatures off Labrador and eastern Newfoundland were low in the 1990s. Starting in the early 1970s, there was a general decline in ocean temperatures, with extremely cold periods in the early 1970s to 1980s and early 1990s, which were followed by very warm conditions in the late 1990s (ICES 2005).

2.2.2 Divisions 4RS

The northern Gulf of St. Lawrence (NAFO Divisions 4RS) is a semi-enclosed sea, where salt-water exchange with the North Atlantic Ocean occurs, along with the inflow of several freshwater rivers (Figure 1.1). The Gulf of St. Lawrence drains into the North Atlantic Ocean to the south-east through the Cabot Strait which has a maximum depth of 480 m. The Gulf also drains to the northeast through the Strait of Belle-Isle, where the depths are less than 60 m. The Laurentian Channel system is the main channel that runs through the Gulf of St. Lawrence with depths from 300-400m. Two other deep channels branch off of this system, the Esquiman Channel that extends towards the Strait of Belle Isle, and the Anticosti Channel extending north of Anticosti Island (Koutitonsky and Bugden 1991).

Temperatures in the Gulf of St. Lawrence are generally above freezing by March-April (Koutitonsky and Bugden 1991). During the summer months surface temperatures range from 12°C to 18°C and by December drop below freezing, at which point ice formation occurs. Over the years, ice cover has been considerable in the Gulf during the winter months. Ice formation and ice cover, has been variable from year to year depending on the air temperatures, wind stresses, and surface currents (Koutitonsky and Bugden 1991).

2.3 Cod biology

2.3.1 Cod in Divisions 2J3KL

The distribution of Atlantic cod in divisions 2J3KL is widespread from the coast outward to the continental shelf and to the nose of the Grand Banks. The cod offshore over winter near the shelf break in 300-500 m extending from Hamilton Bank (Division 2J) to the Nose of the Grand Bank (Division 3L). During the spring or summer these cod begin to migrate inshore into coastal waters where they feed on capelin *(Mallotus villosus*) (Lilly and Murphy 2004). Spawning occurs from March up to April- May along the continental shelf, on the plateau of the Grand Bank and also in inshore waters within bays. "Cod spawning in northeast Newfoundland division 3K commonly begins in March and mainly occurs in April to early May with some spawning continuing to June"(Lilly and Murphy 2004, ICES 2005).

Growth rates in the 2J3KL cod stocks vary temporally and spatially. Cod showed a north-south cline in the growth rate in the 1960s and earlier. The growth rate was lowest off southern Labrador (division 2J), and the highest on the Grand Banks (division 3L). These differences in growth rate have been attributed to difference in temperature (ICES 2005). An increasing surface temperature was observed on a north to south trend. Cod also have different feeding behaviors throughout 2J3KL. Cod off of Labrador do not actively feed during parts of the winter and spring, however cod on the northern Grand Bank do have continual access to prey, and therefore grow at a faster rate (ICES 2005).

Growth rate declined during the early 1980s and again in the early 1990s, especially in 2J (ICES 2005). The growth rate and physiological condition in 2J3KL Atlantic cod have steadily decreased since 1988-1989. These decreases can result from any of several factors including size selective fishing pressure, low temperatures and decrease in available prey. Based on Figures 6 and Figure 7 in Krohn *et al.* (1997), the growth rate ranged between 0.4 to 0.52 kg/yr for 1kg cod from 1978 to 1994, and declined to approximately 0.23 in 1992 (Krohn *et al.* 1997). Much of the variability in growth rate has been attributed to the variability in water temperature (Krohn *et al.* 1997).

The condition factor for the 2J3KL cod stock has varied over time, divisions and age classes (ICES 2005). The condition factor based on liver in relation to gutted weight in cod off of southern Labrador (division 2J) decreased in the early 1990s. The condition factor returned to a normal level in the late 1990s. Cod in division 3K showed a similar pattern in their gutted condition to those in southern Labrador (division 2J). However, in division 3L, the cod condition factor showed an increase in the early 1990s, and has since returned to a normal level (ICES 2005). Based on Figures 6 and Figure 7 in Krohn *et al.* (1997) the condition factor from 1978 to 1993 for all age classes combined in 2J3K, fluctuated between 0.75 and 0.80 before declining in 1989 to a condition factor of 0.7 and increasing to 0.76 in 1994.

2.3.2 Cod in Divisions 4RS

The distribution of cod in the Gulf of St. Lawrence is widespread as migration occurs over long distances every year. In the eastern Gulf cod migrate from the Cabot Strait off southwestern and southern Newfoundland to the north coast of Quebec. During

the winter season they aggregate near the Cabot Strait, at depths of more than 400 m. In April-June spawning takes place when cod first enter the Gulf of St. Lawrence and aggregate in large shoals. Spawning migrations concentrate near the Port au Port Peninsula, off the west coast of Newfoundland (Division 4R) and lower north shore of Quebec (Division 4s) where spawning begins. In the spring and summer months Gulf cod continue to spawn as they migrate towards the Strait of Belle Isle, along the north coast of Quebec, where feeding begins during the summer months (Ouellet *et al.*1997, Dutil *et al.* 2005). In the early 1990s the winter surveys in the Gulf of St. Lawrence found higher concentrations of cod than in the past. Over 90% of the winter biomass was found in deeper waters near the Cabot Strait (Fréchet and Gagnon 1993, Chouinard and Frechet 1994).

The growth rate in northern Gulf cod has been low since the early 1990s, and the stock has been depleted with few fish age 10 and over. Research surveys have verified that length at age, and weight at age decreased in the 1980s and 1990s (Chouinard and Frechet 1994, Dutil *et al.* 2005). In the late 1990s the growth rate increased again. The growth rate varies annually, and seasonally. The growth rate of cod in the northern Gulf becomes negative during the late winter and early summer, and becomes positive during the summer (Dutil *et al.* 2005).

The condition factor of northern Gulf cod was on average low from 1972-1996 ranging from 0.84-1.08 in the autumn months. The condition factor peaks in the fall months and reaches a low in the spring, once the spawning season has started. Low condition and high mortality rate can be attributed to the lack of food during the winter months (January- April) (Dutil *et al.* 2005).

In the 1980s and 1990s the fish condition factor declined and averaged between 0.6-0.7 during the spring months. The condition and energy reserves of northern Gulf cod declined for several consecutive years (1990-1994) (Lambert and Dutil 1997) .Low condition factors can cause an increase in natural mortality due to low energy levels, and an increase in susceptibility to disease. Low condition factor can also decrease metabolic capacities and growth rates and, as a result, reduce swimming capacity which could affect their ability to escape predators and fishing gear, and ability to capture and feed on prey (Dutil *et al.* 2005, Lambert and Dutil 1997).

Chapter 3: Methods

3.1 Annual Random Stratified Bottom Trawl Surveys

For both the 2J3KL and 4RS surveys, a stratified design was used whereby the stratification scheme is based on depth intervals intercepted by latitude and longitude (Doubleday 1981, Lilly 1994). Each depth stratum had a minimum of 2 randomly chosen sets (tows). The number of sets is approximately proportional to the stratum area, with the provision that each stratum be allocated at least 2 sets (Doubleday 1981, Castonguay *et al.*1999, Lilly 1994).

3.1.1 2J3KL Autumn Surveys

The random depth-stratified bottom trawl surveys were conducted by Fisheries and Oceans Canada (DFO) in Divisions 2J, 3K, and 3L (Figure 3.1) during the late autumn season (October-December). The trawl survey area in NAFO Divisions 2J, 3K, and 3L covers the southern Labrador Shelf, the Northeast Newfoundland Shelf, the northern Grand Bank, and the adjacent continental slope to a maximum depth of 1000 meters (Lilly, 1994). These surveys were primarily offshore (minimum depths approximately 200m) and they took place from 1978 onwards in Divisions 2J and 3K, and 1981 onwards in Division 3L (Lilly *et al.* 2003).

Until 1994, the RV Gadus Atlantica, was used to conduct the autumn surveys in Divisions 2J and 3K. Surveys in Division 3L were conducted by RV A.T. Cameron (1971-1982) and RV Wilfred Templeman or its sister ship RV Alfred Needler (1983-

2000). In most recent years the RV Teleost has been used to conduct the surveys in 2J3KL.

During the autumn of 1995 the Campelen 1800 shrimp trawl with rockhopper was used for the first time, replacing the Engels 145 Hi-rise bottom trawl that had been used since the start of the surveys in 2J and 3K and since the change to the RV Wilfred Templeman in Division 3L (Lilly *et al.* 2003).

The Engel trawl was towed for 30 min. at 3.5 knots, while the Campelen was towed at 3.0 knots for 15 min. at each station. Fishing in all divisions and years was conducted on a 24 hour basis (Lilly 1994). To account for the change in gear in 1995, the research vessel data have been standardized to the number of fish per standardized tow (0.8 of a kilometer distance).

3.1.2 4RS Winter Surveys

Random depth-stratified bottom trawl surveys were conducted by Fisheries and Oceans Canada in Division 4RS, during the winter months (January- February) from 1978-1994 excluding 1982. The trawl survey area in NAFO Divisions 4RS extends from the Cabot Strait to the Strait of Belle Isle, including the Anticosti and Laurentian Channels (Figure 1.1). This winter survey was conducted on board the RV Gadus Atlantica while using an Engel 145 Hi-rise bottom trawl with a 30-mm liner (Dutil *et al.* 1999). The number of stations ranged from 84-207, with an average of 147 stations, tows were of a 30-min. duration at 3.5 knots (Castonguay *et al.* 1999).

3.2 Length to Age conversion

I obtained length frequency data for the years of 1978- 1994 from Fisheries and Oceans Canada Newfoundland Region (2J3K) (Division 3L 1981-1994) and Quebec Region (4RS). These data were formatted to reduce the number of variables required to complete my analysis using SAS programming and Microsoft Excel spreadsheets. I used the Von Bertalanffy model (1938) to convert the length frequencies to age classes (Hilborn and Walters, 1992). The Von Bertalanffy model is as follows:

$$L_t = L\infty\,[1 - e^{-K\,(t - to)}] \qquad (1.1)$$

This model has three parameters, L∞ defines the maximum body size, K is called the Brody growth coefficient, which defines the growth rate towards the maximum size, and t_o shifts the growth curve along the age axis to account for any nonzero body length at age zero (Hilborn and Walters, 1992). In order to compute ages from lengths, I reorganized the Von Bertalanffy equation so that age was a function of length as follows.

$$
\begin{aligned}
Lt &= L\infty\left[1-e^{-k(t-to)}\right] \\
\frac{Lt}{L\infty} &= 1-e^{-k(t-to)} \\
\frac{Lt}{L\infty}-1 &= -e^{-k(t-to)} \\
1-\frac{Lt}{L\infty} &= e^{-k(t-to)} \\
\frac{L\infty-Lt}{L\infty} &= e^{-k(t-to)} \\
\ln\left(\frac{L\infty-Lt}{L\infty}\right) &= \ln\left(e^{-k(t-to)}\right) \\
\ln\left(\frac{L\infty-Lt}{L\infty}\right) &= -k(t-to) \\
\ln\left(\frac{L\infty-Lt}{L\infty}\right)*\frac{1}{-k} &= (t-to) \\
(t-to) &= \ln\left(\frac{L\infty-Lt}{L\infty}\right)*\frac{1}{-k}
\end{aligned}
\tag{1.2}
$$

The length frequencies from 2J, 3K, and 3L for 1978-1991 were divided into 3-cm intervals and into 1-cm intervals for the data from 1992-1994. These length frequencies were converted to age classes (<2-12+) by combining equation 1.2 with age length keys for each division as described below. The age length key for 2J3KL was obtained from Lilly *et al.* 2003. The age length key for divisions 4RS was provided by Alain Frechet, Fisheries and Oceans, Quebec Region. The length frequency data from 4RS for 1978-1994 were divided into 3-cm intervals.

The Von Bertalanffy ratios {Ln (L_∞- L_t)/ L_∞} were computed for each length that appeared in each age length key. For each of the areas the L_∞ was based on the maximum lengths observed in each dataset. The ages (t-t_0 - Eq. 1.2) from the age/length keys were

regressed against the Von Bertalanffy standardized ratios ($\frac{Lt}{L\infty}$ in Eq. 1.2) to produce linear equations that express age as a function of standardized length ratio for each division and year. These linear equations allowed me to compute the ages of fish whose lengths are listed in the length frequency data set. Once the ages were calculated they were rounded to the nearest whole year (age). Fish ages less than and equal to 2 were grouped into <2. Fish ages that were age 12 and older were grouped as 12+. The counts associated with each of the ages or groups were totaled.

Fisheries and Oceans Canada use a similar age-length key analysis, which is comparable to the Von Bertalanffy. DFO constructs an age length key from a representative sample of fish from a population. This is called a double frequency table, with age in the columns and lengths in the rows. A table is then constructed giving the percentage of each age among fish of a given length, and this is used to convert any observed length distribution to age (Ricker 1975).

3.3 Age groups

To take into account degree of maturation, I grouped all ages (<2-12+) into 4 age groups (ages ≤ 2, ages 3-4, ages 5-6 and ages 7-12+). The age groups were set up based on proportion of mature values from Table 36 in Lilly *et al.* 2003. For age group ≤2 proportion mature was less than 0.2 %, ages 3-4 ranged between 1 to 10%, ages 5-6 ranged from 4% to 95% (proportion mature increased with time), and ages 7-12+ proved to be the most prominent spawning group and ranged from 75% to 100%, with most values >90% (Lilly *et al.* 2003).

3.4 Analysis

3.4.1 Distribution Maps

I mapped the 4 age groups (ages ≤ 2, ages 3-4, ages 5-6 and ages 7-12+) for each consecutive year (78-94) in Divisions 4RS, and Divisions 2J3KL. The counts per standardized tow were displayed in ranges (0 to 10, 000) for Divisions 2J3KL, and the counts per nautical mile were displayed in ranges (0 to 10,000) for Divisions 4RS. These maps were visually interpreted by constructing a narrative for each year in all divisions.

3.4.2 Gini Index

The Gini index, which is commonly used as a measure of income distribution, is defined as the area between the Lorenz Curve of the distribution and the identity function as shown in Figure 3.1 (Dagum 1985, Dixon *et al.* 1987). I calculated the Gini Index using Lorenz curves. To construct these Lorenz curves I calculated the Gini index using the Brown Formula (Brown 1994), which is as follows:

$$G = \left| 1 - \sum_{k=1}^{n} (X_k - X_{k-1})(Y_k + Y_{k-1}) \right| \qquad (1.3)$$

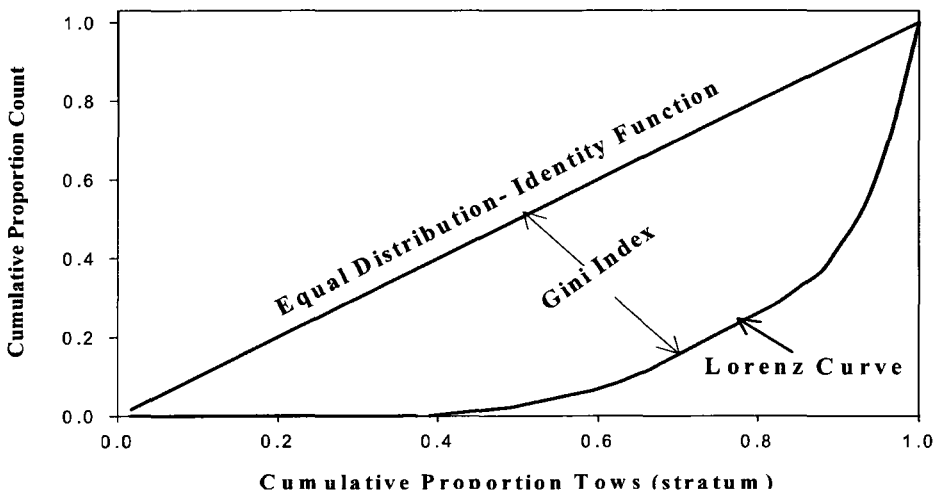

Figure 3.1 Lorenz Curve for the cumulative proportion of tows and cumulative proportion of fish counts. The Lorenz curve bends downwards and to the right within the unit square as cod become more aggregated. If fish were equally distributed among tow locations, the Lorenz curve would be the identity function (diagonal straight line).

This equation consists of 3 variables, G represents the Gini coefficient, X represents the cumulative proportion of tows, and Y represents the cumulative proportion of fish counts. The Gini index is the Gini coefficient expressed as a percentage, and is equal to the Gini coefficient multiplied by 100 (Dagum, 1985, Dixon *et al.* 1987).

The Gini index was calculated among tow locations for each age and for age groups ≤ 2, 3-4, 5-6 and 7-12+ within each consecutive year (78-94) for Divisions (2J3K and 4RS) and division 3L (81-94) within the study area (Figure 1.1).

3.4.3 Variance-Mean

I calculated the variance and mean count per tow for each age and for age groups ≤ 2, 3-4, 5-6 and ages 7-12+ within each consecutive year (78-94) for all Divisions (2J3KL and 4RS).

The variance (var (C)) is defined as:

$$Var(C) = \frac{\sum (C - \overline{C})^2}{(n-1)} \tag{1.4}$$

where C is the count per tow and n is the number of tows. Variance and mean count per tow were plotted against time within each age group for all divisions in the study area.

3.4.4 Power Law Exponent

The relation between the spatial variance and the mean can be quantified as a power law (Perry 1981) (Horne and Schneider 1995) where the exponent measures the strength of spatial aggregation, scaled to the mean. I estimated the exponent of the power law by regressing the common log of the variance (y-axis) to the common log of the mean (x-axis) (Figure 3.3) for each age class and all years (78-94) using SAS programming, and SigmaPlot. I used the slope (exponent of the power law) from each age class to graph trends over time and over age classes.

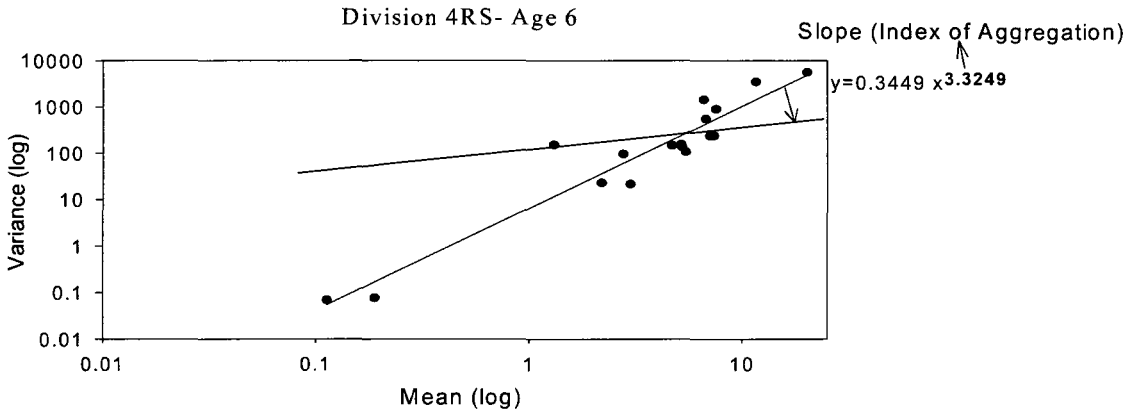

Figure 3.2 The Power law of Age 6 cod in divisions 4RS. The slope is used as a measure of aggregation, as the slope increases the index of aggregation increases.

3.4.5 Frequency Distributions and Cumulative Frequency Distributions

As fish become more aggregated, the frequency distribution becomes heavier in the right tail (positively skewed) and the cumulative frequency distribution rises more slowly on the right than the left side of the mean values (Refer to Appendix B). Frequency distributions and cumulative frequency distributions were compared visually for all age groups (<2-12+) within each consecutive year (78-94). Skewness was calculated as a measure of frequency distributions and in turn measure aggregation. Skewness characterizes the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values, therefore the more positive the skewness, the more prominent the tail, and the higher the aggregation.

The equation for skewness of count per tow (skew (C)) is defined as:

$$Skew(C) = \frac{n}{(n-1)(n-2)} \sum \left(\frac{C - \overline{C}}{s} \right)^3 \qquad (1.5)$$

where n is the number of tows, s is the standard deviation of the counts $s = \sqrt{\text{var}(C)}$. These indices were calculated for all ages (<2-12+) for all years (78-94) within the study area.

Chapter 4: Results

4.1 Trends in Atlantic Cod Distribution based on distribution maps

In this section I explore the distributional shifts and change in aggregation of Atlantic cod age groups (ages $\leq$2, ages 3-4 ages, 5-6 and age 7-12+) from 1978 to 1994, divisions 2J3KL (Figures 4.1 to 4.17) and 4RS (Figures 4.18 to 4.33) by using distributional maps based on the random depth-stratified bottom trawl surveys. In divisions 2J3KL these surveys were not conducted in division 3K until 1981. Refer to Figure 1.1 as a reference guide to geographic locations and NAFO divisions which are mentioned throughout the following narrative.

4.1.1 Distribution maps for Divisions 2J3KL

Juvenile cod (ages $\leq$ 2 years old) from 1978-1979 showed a low abundance (counts with <10 cod per standardized tow) in research vessel survey data off the coast of Labrador approximately near latitude 53° N (Figure 4.1 to Figure 4.2). Most of the juvenile cod were caught in division 2J along the Hamilton Bank. In 1980 and 1981 (Figures 4.3 and 4.4) the distribution of the juvenile cod shifted south towards division 3K, close to latitude 50° N, leading into 1982 (Figure 4.5) where the distribution shifted into division 3L closer to the Grand Bank. The survey in 3L did not start until 1982, therefore no cod distribution would have shown up here. In 1983 and 1984 (Figure 4.6 and Figure 4.7) an increase in aggregation off the coast of Labrador close to latitude 54°

N. This aggregation showed a density of counts >50 cod per standardized tow. From 1985 to 1988 (Figure 4.8 to Figure 4.11) there was a small number of tows with counts >20 cod per standardized tow in division 3K across the continental shelf. In 1989 (Figure 4.12) cod started to show signs of aggregation with an increase in amount of tows with counts >50 cod per standardized tow off the coast of Labrador near the continental shelf break (between latitude 50° N and 55° N).These aggregations dissipated in 1990 (Figure 4.13). From 1991 to 1994 (Figure 4.17) there was no sign of aggregation, and a high number of counts with 0 fish.

Cod ages 3-4 aggregated near the Hamilton Bank off the coast of Labrador (approximately latitude 55° N) in 1978 (Figure 4.1) with a high amount of tows showing counts > 50 cod per standardized tow. In 1980 and 1981 (Figures 4.3 and 4.4) there was no sign of aggregation and the counts remained on average lower than 40 cod per standardized tow. In 1982 (Figure 4.5) aggregation is again evident off the coast of Labrador near latitude 55° N, leading into 1983 (Figure 4.6), where cod showed signs of aggregation not only near latitude 55° N (near Hamilton Bank), but also in division 3L, near the Grand Bank approximately longitude 50° W, with counts > 50 cod per standardized tow. In 1984 (Figure 4.7) there was no survey in division 3L, and the cod again showed aggregation near Hamilton Bank (approximately near latitude 55° N). From 1985 to 1986 (Figure 4.8 and Figure 4.9) aggregations of cod ages 3-4 were consistently found in division 2J (approximately latitude 53° N and 54° N), but the cod distribution became widely spread in 1987 (Figure 4.10) when cod were distributed throughout 2J3KL. In 1988 (Figure 4.11), cod aggregation is shown near the continental shelf break, at approximately latitude 48N (division 3L) and again in 1989 (Figure 4.12)

with additional aggregations along the continental shelf break near latitude 52° N and near the Grand Bank at approximately longitude 50° W. Before the closure of the northern cod fisheries in 1990 and 1991 (Figure 4.13 and 4.14) cod ages 3-4 formed aggregations along the continental shelf break near latitude 52° N in divisions (approximately latitude 48° N and 52°-53° N). These aggregations were prominent in a fixed location along the shelf break in 3KL (Bonavista corridor), and their size started to shrink between 1992 and 1994 and they eventually disappeared by 1994 (Figures 4.14 to 4.17).

Cod ages 5-6 showed signs of aggregation in 1978 (Figure 4.1) along the continental shelf break near latitude 55° N in division 2J with aggregations of few high counts (>200 cod per standardized tow). In 1979 (Figure 4.2) there was a slight change in aggregation, and the aggregations with counts more than 300 cod per standardized tow were found between Funk Island Bank, and the Strait of Belle Isle, approximately latitude 52° N. These aggregations were not as apparent in 1980, however in 1981 cod ages 5-6 showed signs of aggregation along the continental shelf break near approximately latitude 55° N in division 2J (Figure 4.4). This aggregation remained consistent in 1982. In 1983 (Figure 4.6) the distribution of cod ages 5-6 showed no strong signs of aggregation. Then in 1984 (Figure 4.7) this age group aggregated again near latitude 55° N, with a few high counts of >100 cod per standardized tow, and also in division 3K near latitude 50° N, and near the Strait of Belle Isle. There were several aggregations of cod ages 5-6 in the 1985 survey results (Figure 4.8). These were found in division 3L, near the Grand Bank, along the continental shelf break near latitudes 48° N, 52° N and latitude 55° N. From 1986 to 1988, (Figures 4.9 to 4.11) larger aggregations were identified in 2J3K and in division 3L

along the shelf near latitudes 48° N, 52° N and latitude 55° N with tows up to 500 to 1000 cod per standardized tow and also near the Grand Bank. These aggregations remained in the same geographic locations until 1988, but decreased in size with 100 cod per standardized tow (Figure 4.11). In 1989 (Figure 4.12) cod ages 5-6 showed the strongest sign of aggregation in division 3K along the continental shelf close to the Funk Island Bank (approximately latitude 52° N) with tows of more than 500 cod per standardized tow with an additional aggregation along the continental shelf break near . The 1990 and 1991 survey results (Figure 4.13 and 4.14) revealed aggregations of age 5-6 cod along the 3KL boundary (approximately latitude 48° N) and in the southern part of 3L near the Grand Bank but no aggregations in 2J. In 1992 (Figure 4.15) the aggregation in 3K disappeared and the aggregation on the 3KL boundary (approximately latitude 48° N) started to shrink. In 1993 these aggregations continued to shrink until 1994 when the cod only showed up in a few research vessel tows with less than 10 cod per standardized tow.

Cod ages 7-12+ were distributed throughout 2J3K in trawl surveys from 1978 to 1981 (Figure 4.1 to 4.4). In 1981 (Figure 4.4) there was a strong sign of aggregation in division 2J along the continental shelf break near latitude 55° N with tows of more than 300 cod per standardized tow. In 1982 (Figure 4.5), cod ages 7-12+ aggregated in divisions 2J and 3K along the continental shelf approximately near latitudes 52° N and 55N. In 1983 (Figure 4.6), the cod were distributed throughout 2J3KL, with a slight sign of aggregation in division 2J, near the Strait of Belle Isle(approximately latitude 53° N) with tows of more than 200 cod per standardized tow. In 1984 (Figure 4.7) this age group aggregated near the Funk Island Bank (approximately latitude 50° N) with a few tows of 50 to 100 cod per standardized tow concentrated in one area. Ages 7-12+ cod were

starting to show more signs of aggregation in 1985 (Figure 4.8) with concentrated groups of tows with 50 to 100 cod per standardized tow near the Hamilton Bank in division 2J (approximately latitude 53° N) and along the continental shelf at latitude 48N. From 1986 to 1988, (Figure 4.9 to 4.11) larger aggregations formed in 2J3KL. In 1986 and 1987, cod ages 7-12+ showed aggregations near the continental shelf break, approximately near latitudes 48° N, 52° N, and 55° N with tows of 500-1000 cod per standardized tow, and also showed signs of aggregation at latitude 53° N near the Strait of Belle Isle. In 1988 (Figure 4.11) cod ages 7-12+ showed a large aggregation near latitude 55° N in division 2J, with a small aggregation along the continental shelf break near latitude 48° N. This large aggregation in 2J, shrinks in 1989 (Figure 4.12), and larger aggregations become prominent along the continental shelf break in division 3K and 3L, approximately near latitudes 48° N and 52° N. In 1990 and 1991 (Figure 4.13 and 4.14) these aggregations again formed along the continental shelf break at the 3KL boundary (approximately near latitudes 48° N, and 52° N) and in the southern part of 3L near the Grand Bank but there were no aggregations shown in 2J these aggregations were large with tows of more than 1000 cod per standardized tow. In 1992 (Figure 4.15) the aggregation in 3K disappeared and the aggregation on the 3KL boundary started to shrink and eventually in 1993 and 1994 (Figure 4.16 and 4.17) there was only a small amount of tows with low counts (less than 10 cod per standardized tow) of cod ages 7-12+ caught.

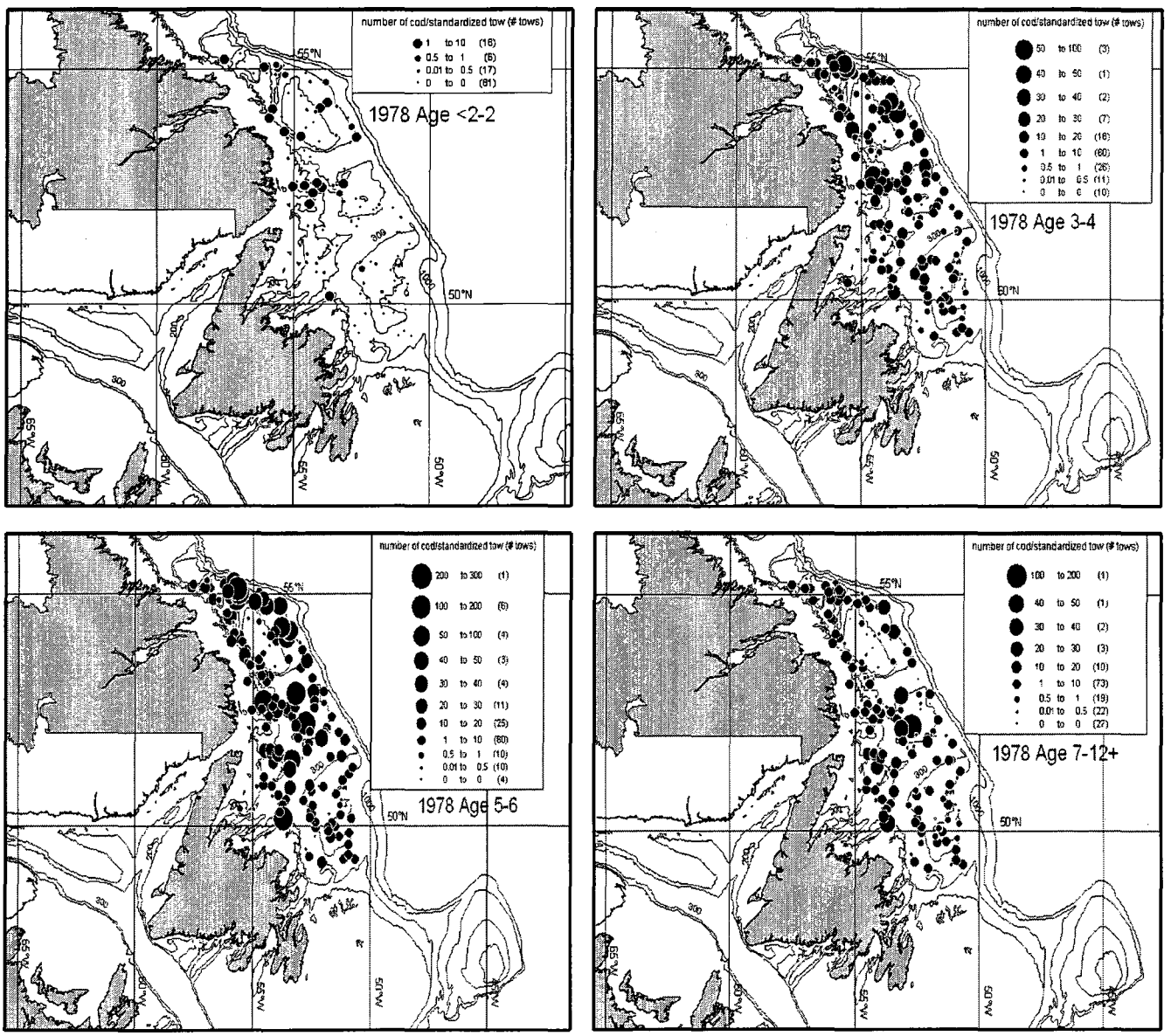

Figure 4.1. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1978.

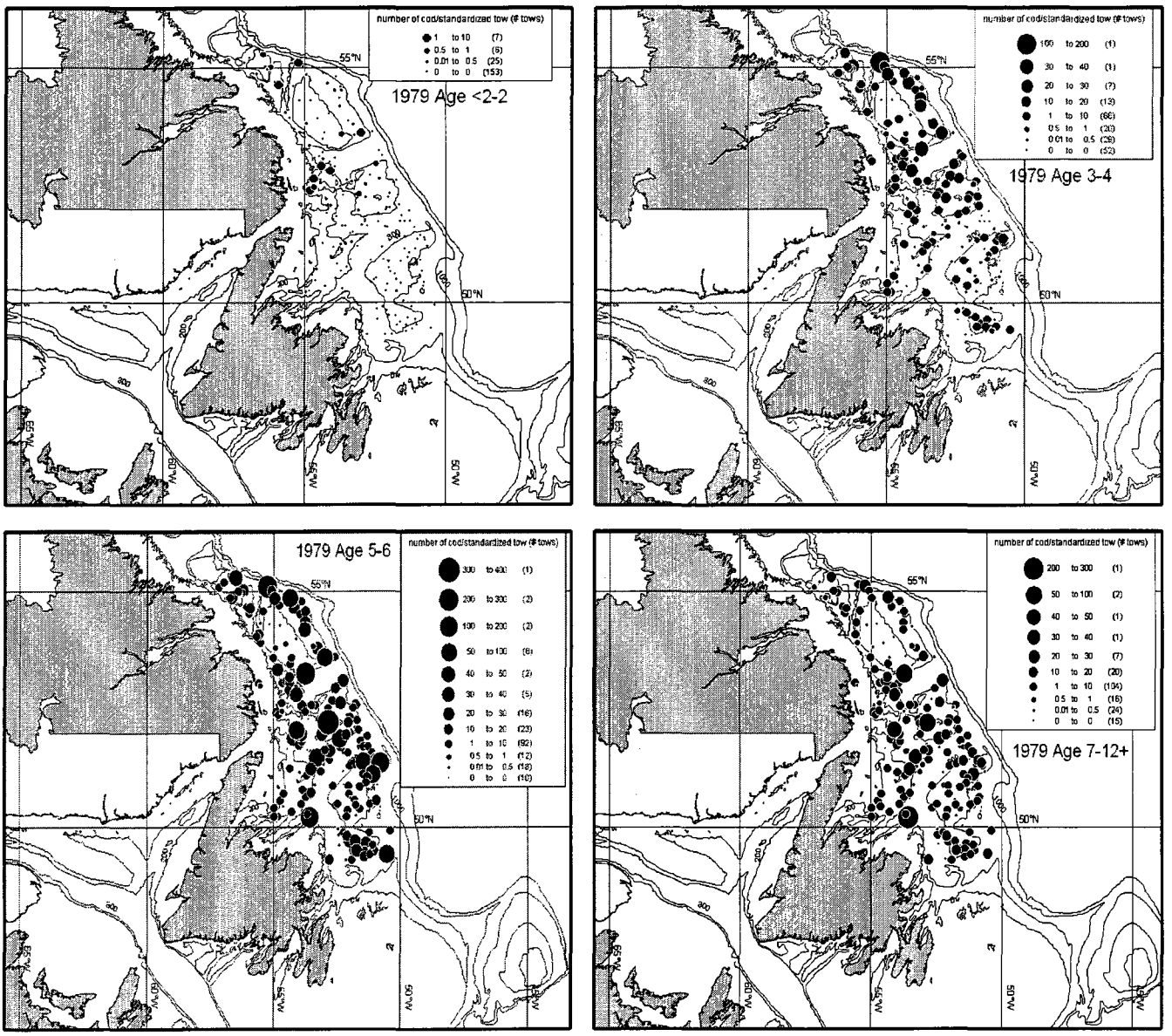

Figure 4.2. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1979.

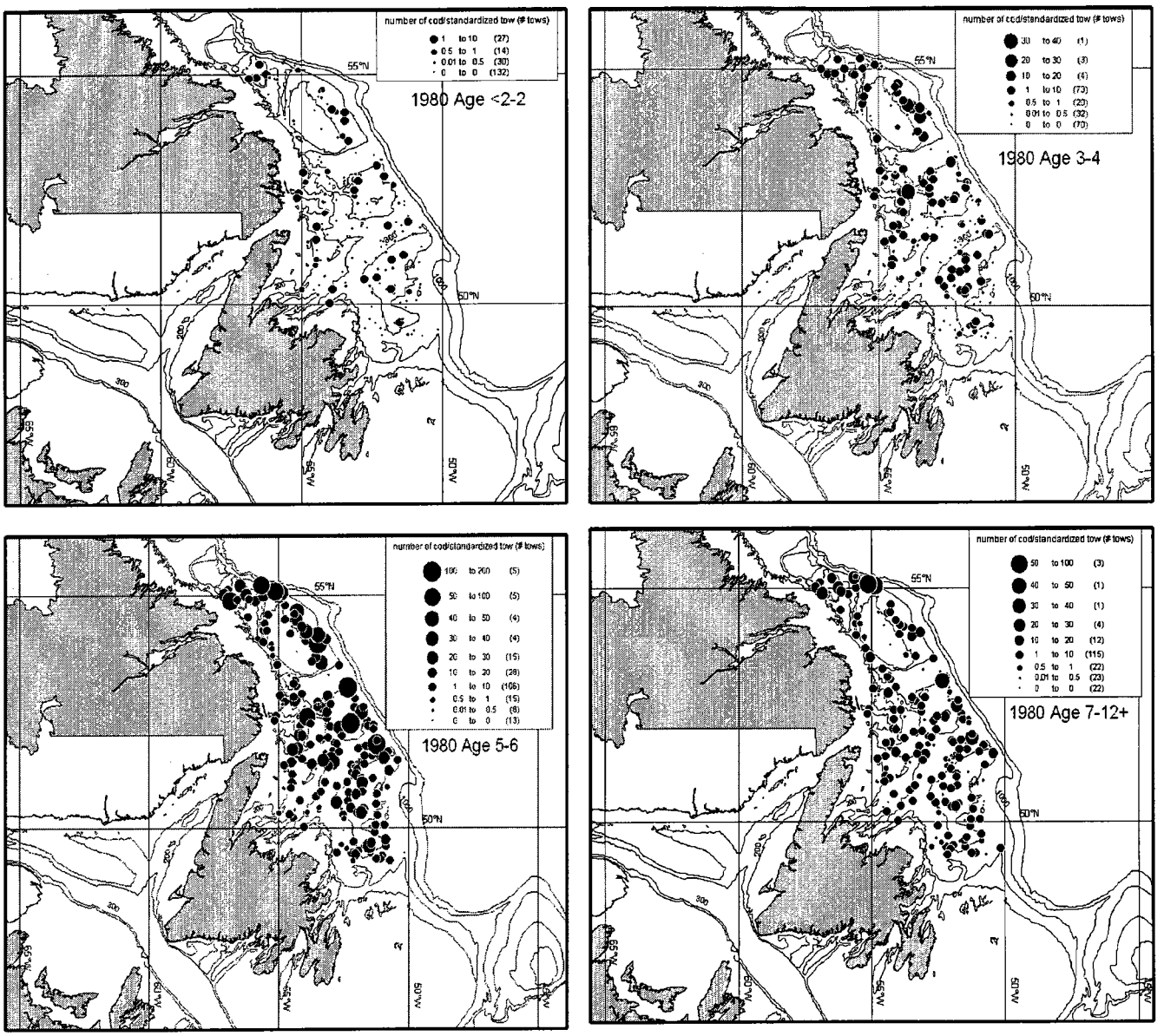

Figure 4.3 Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1980.

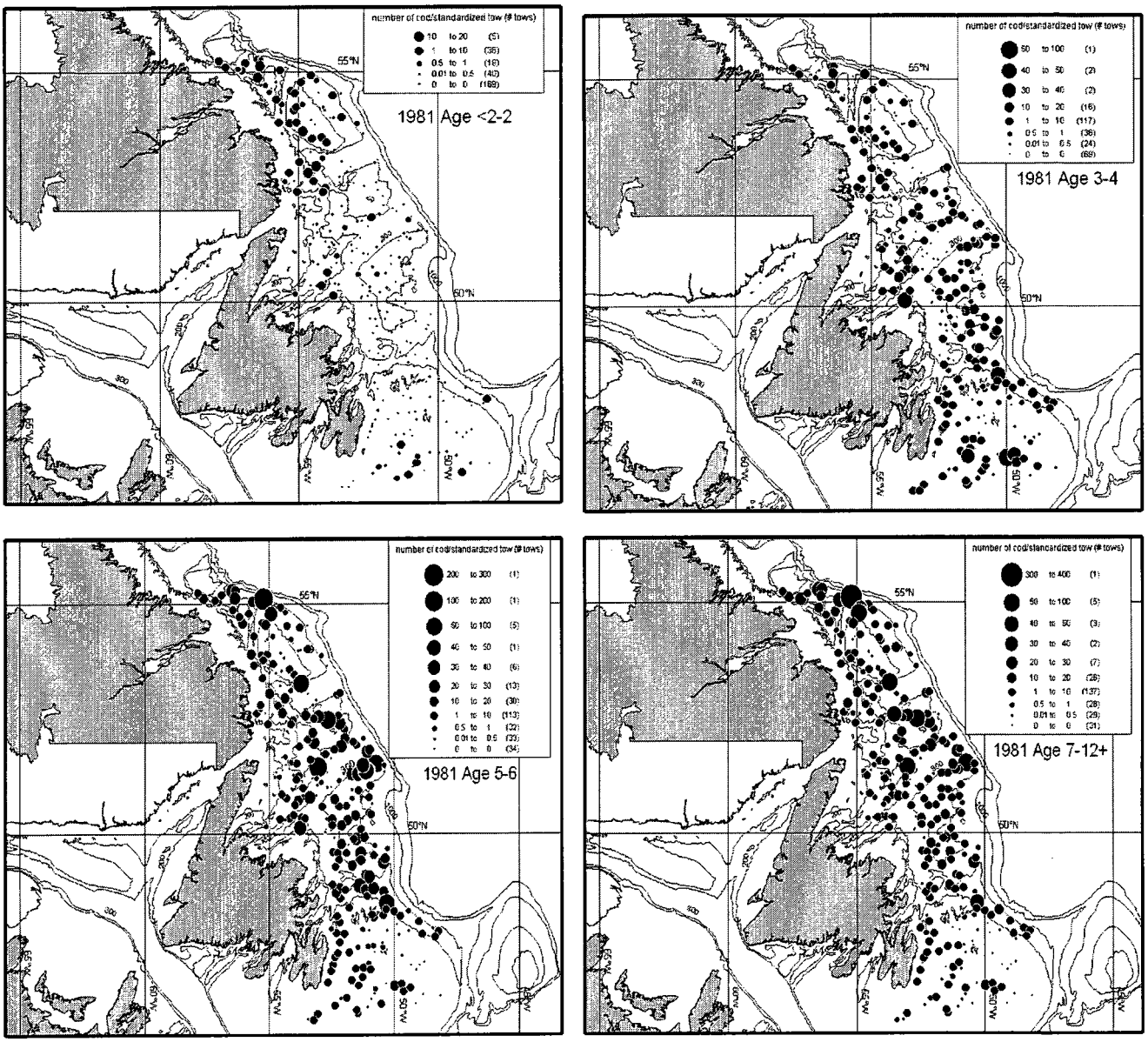

Figure 4.4. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1981

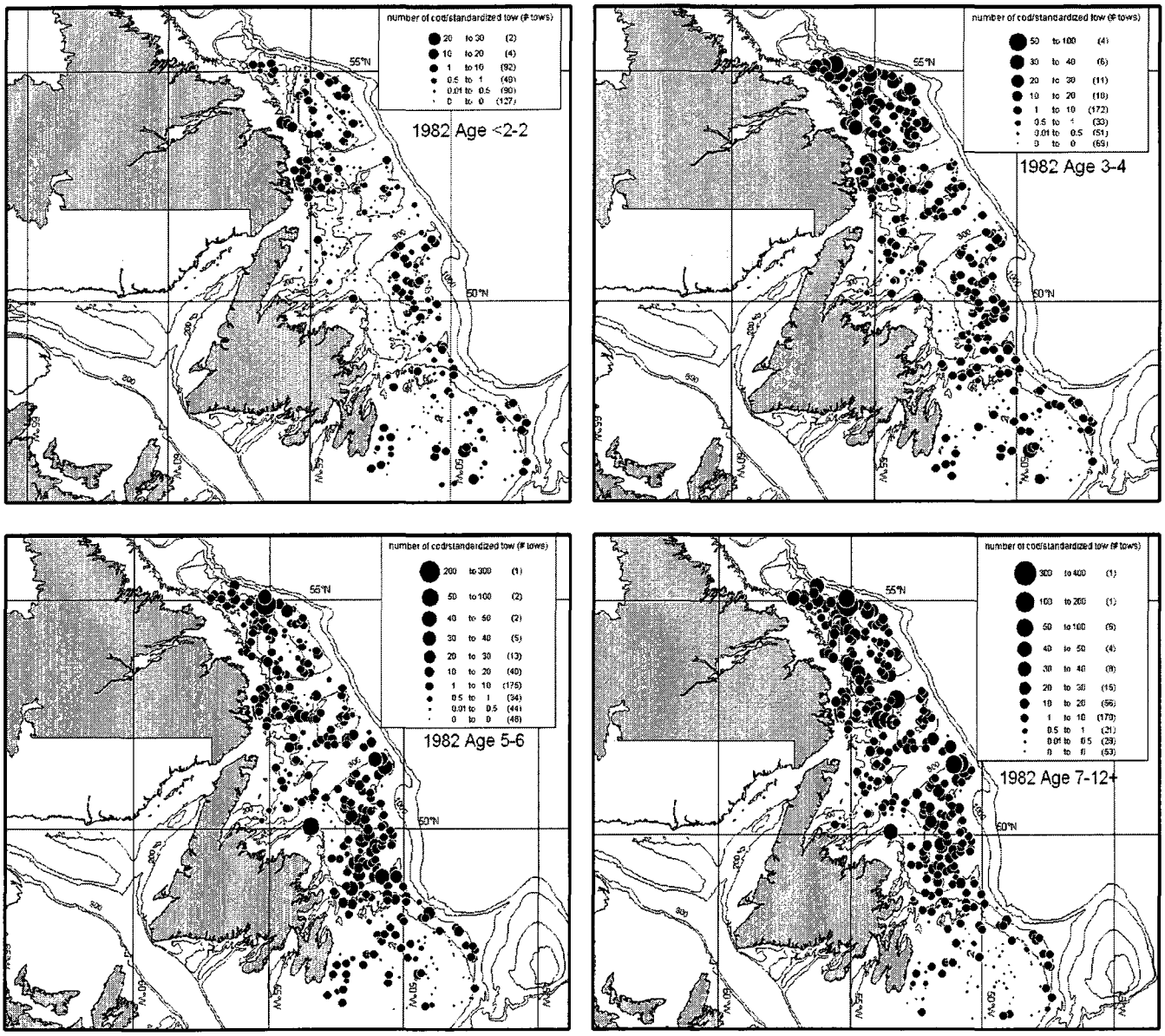

Figure 4.5 Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1982

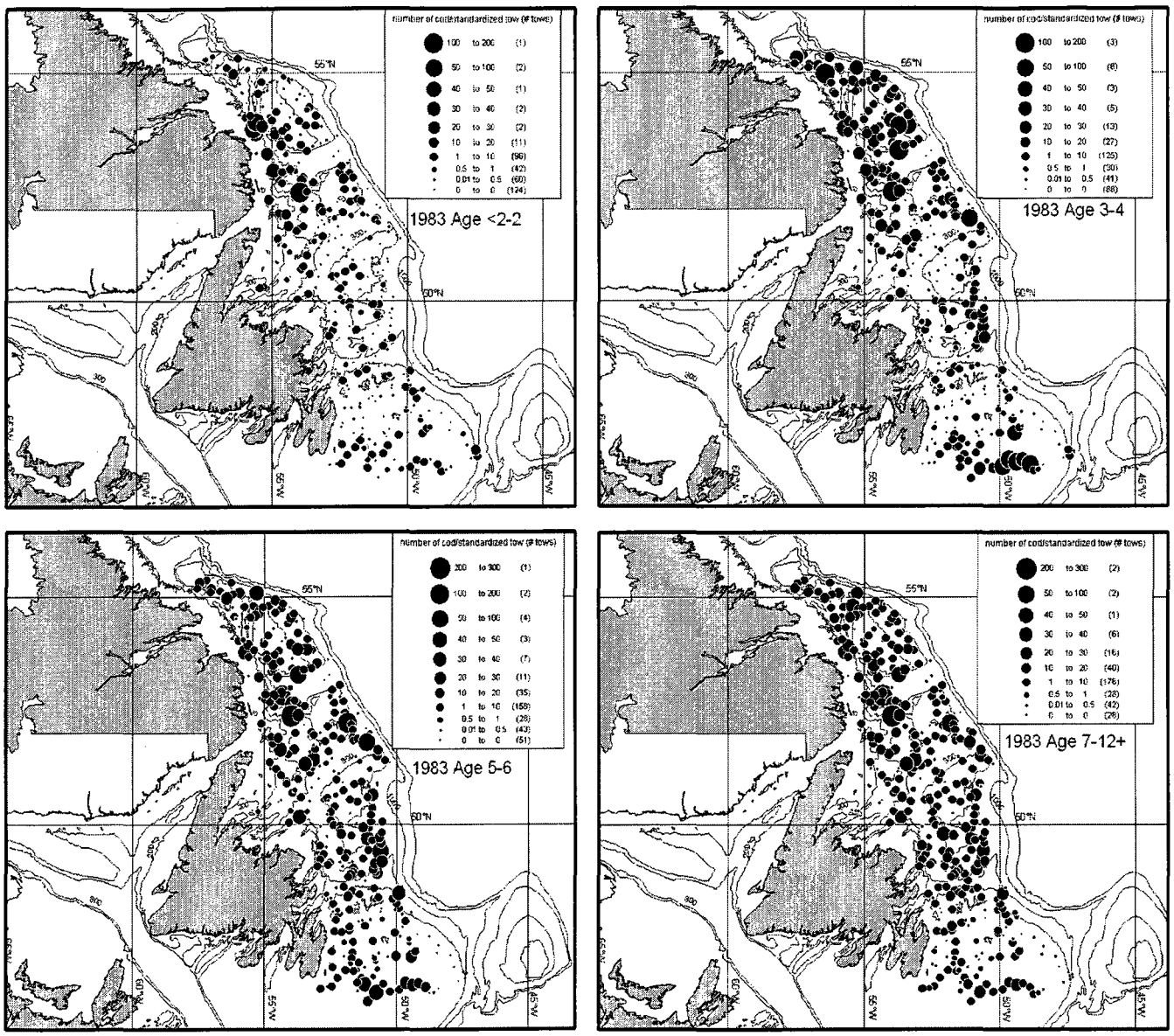

Figure 4.6 Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1983

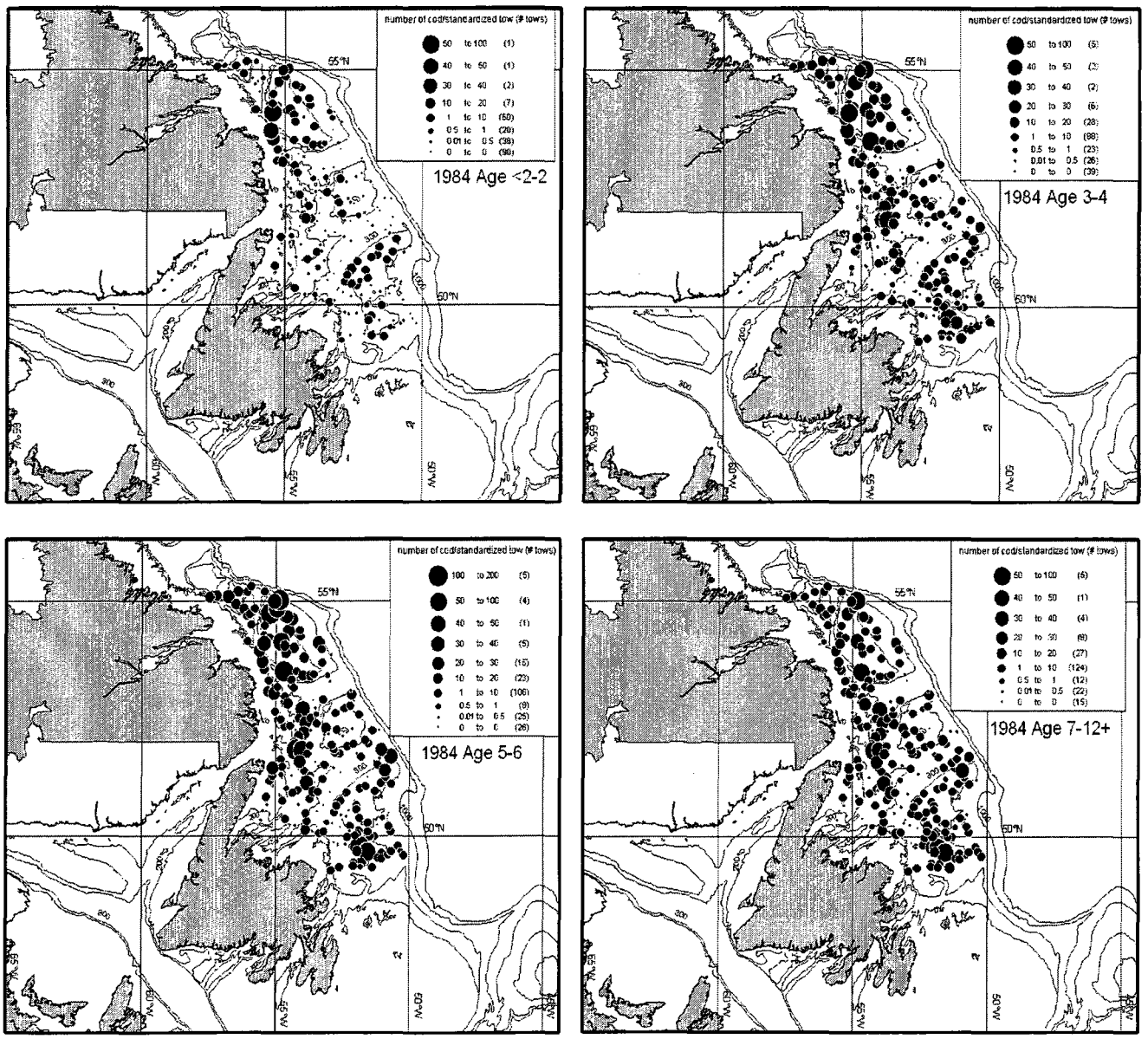

Figure 4.7. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1984.

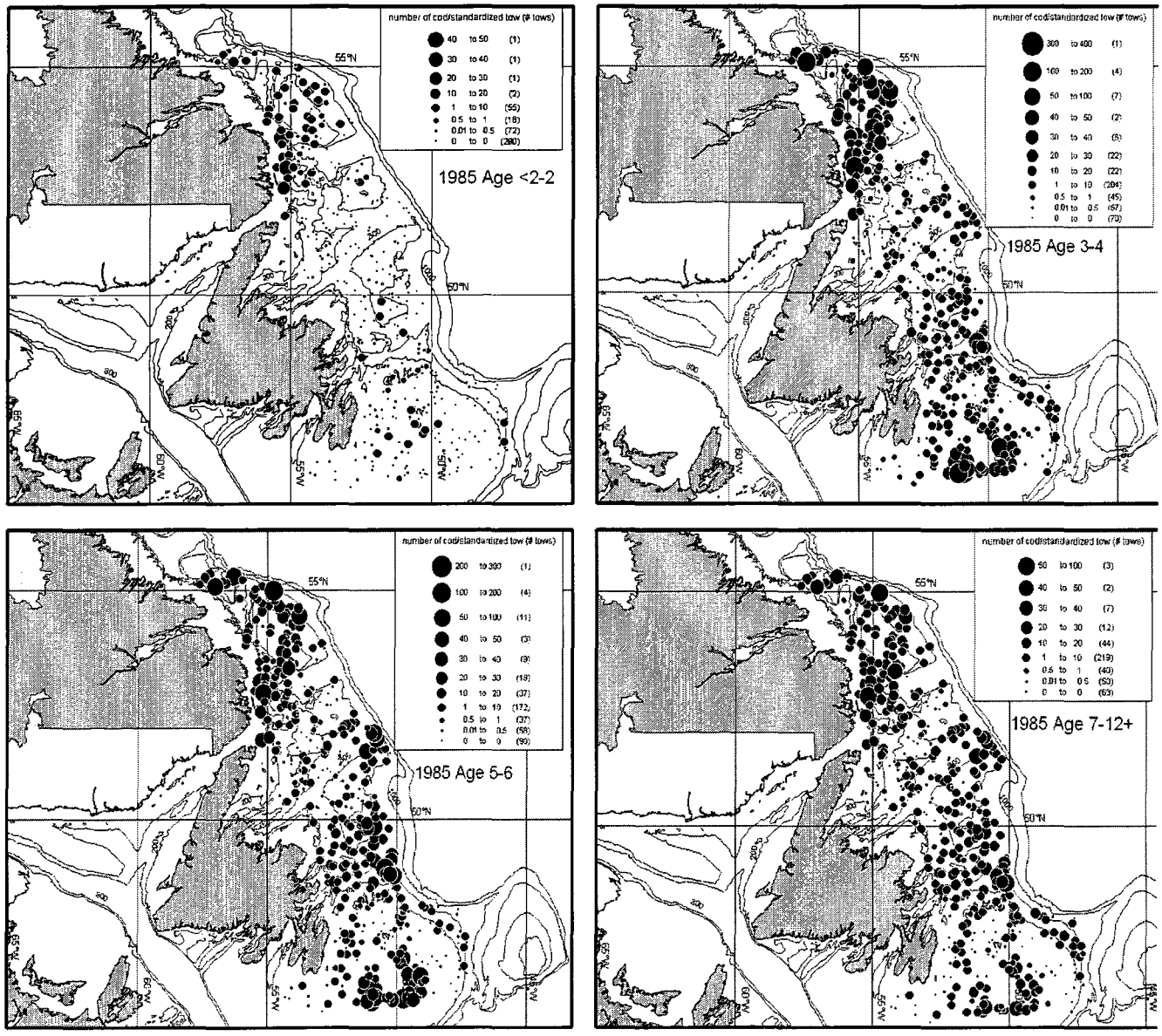

Figure 4.8. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1985.

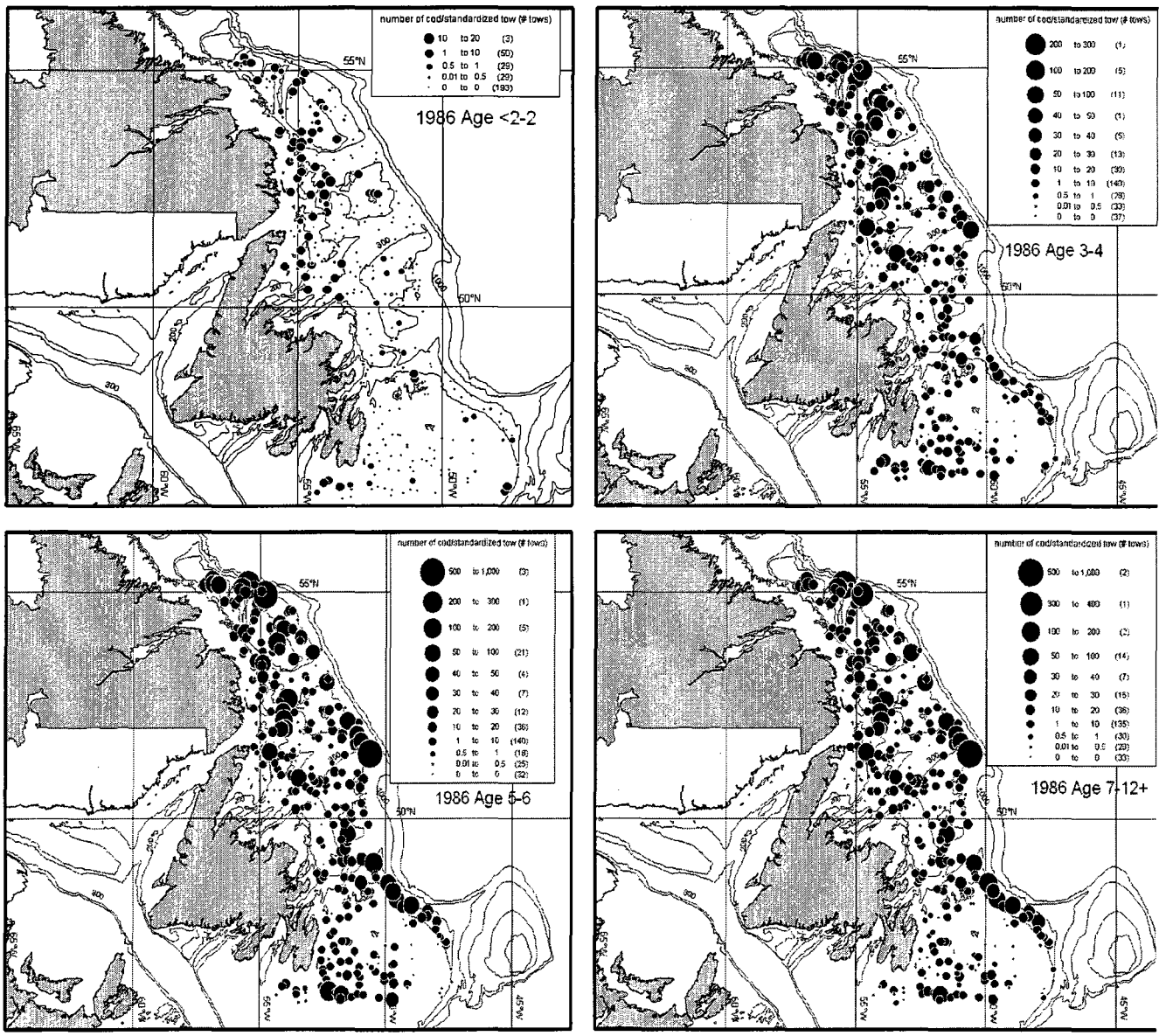

Figure 4.9. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1986.

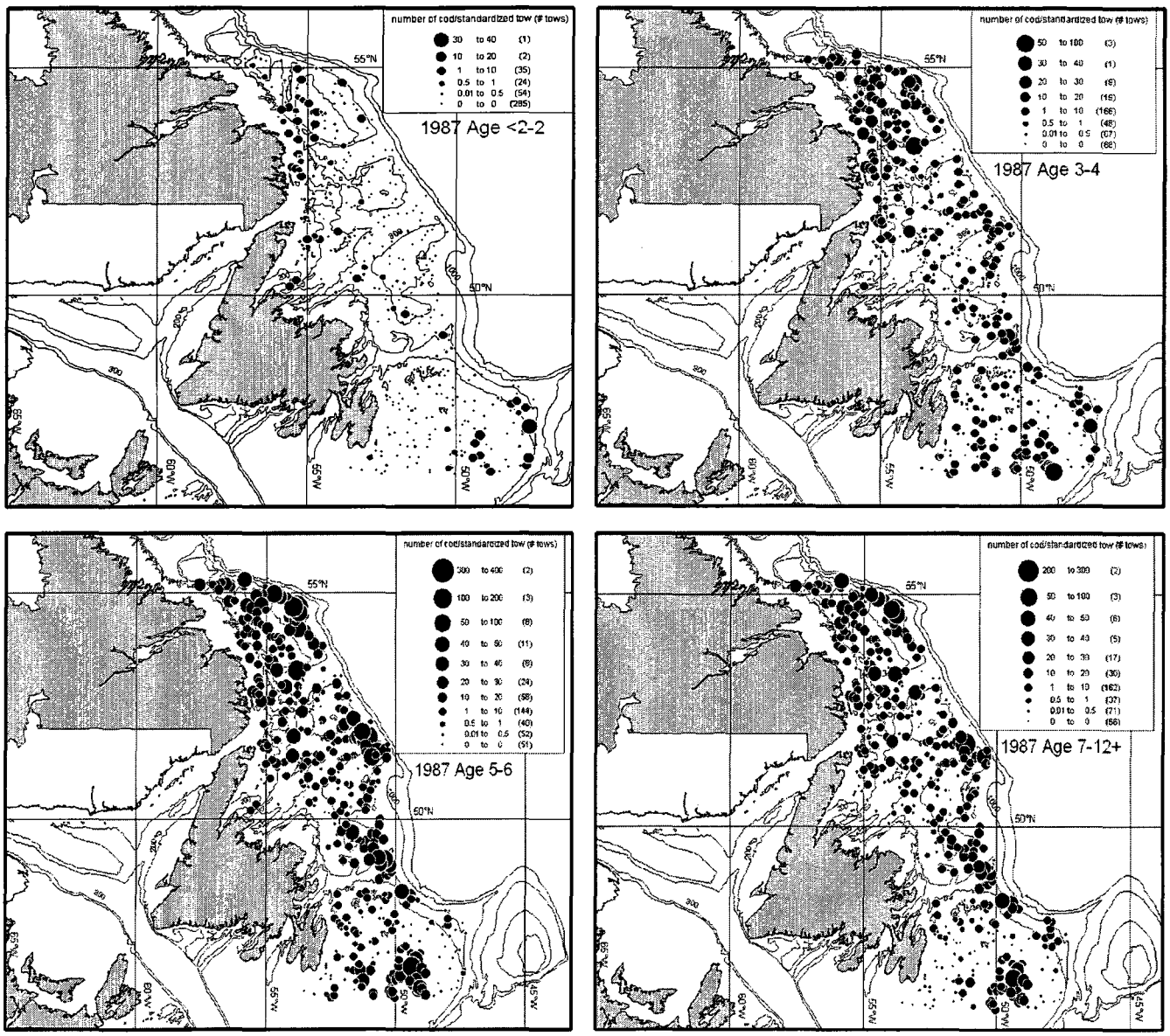

Figure 4.10. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1987.

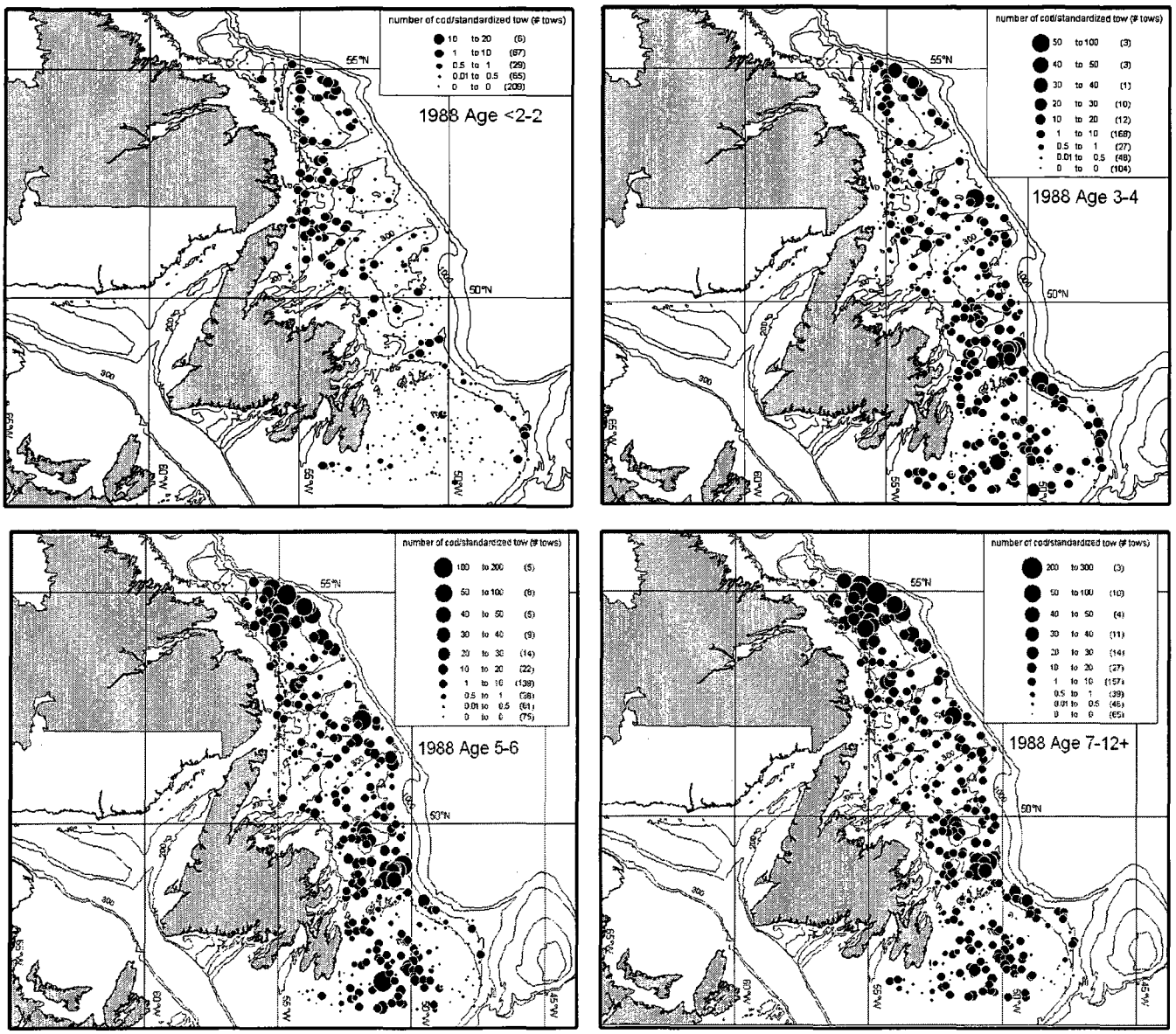

Figure 4.11. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1988.

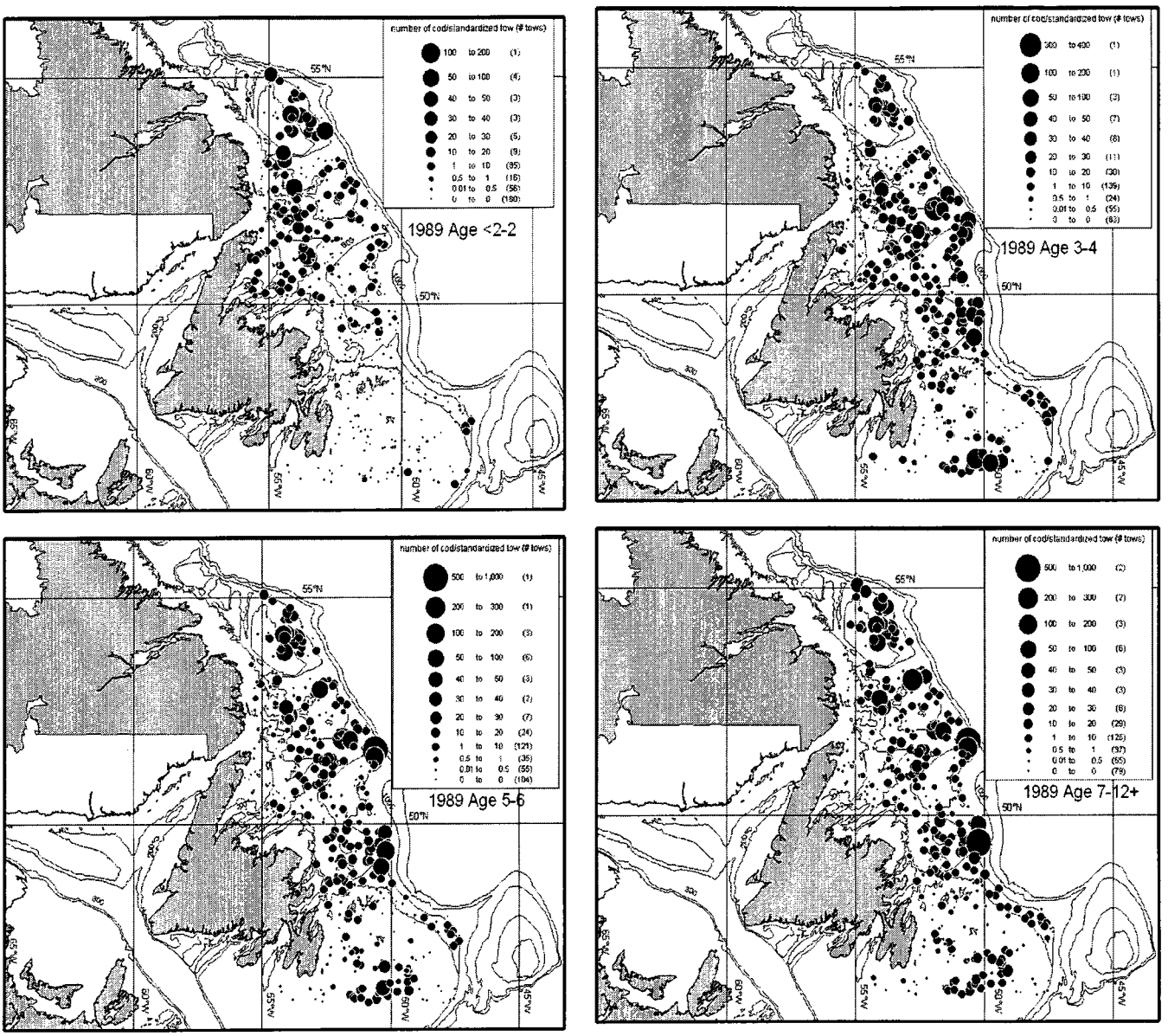

Figure 4.12. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1989.

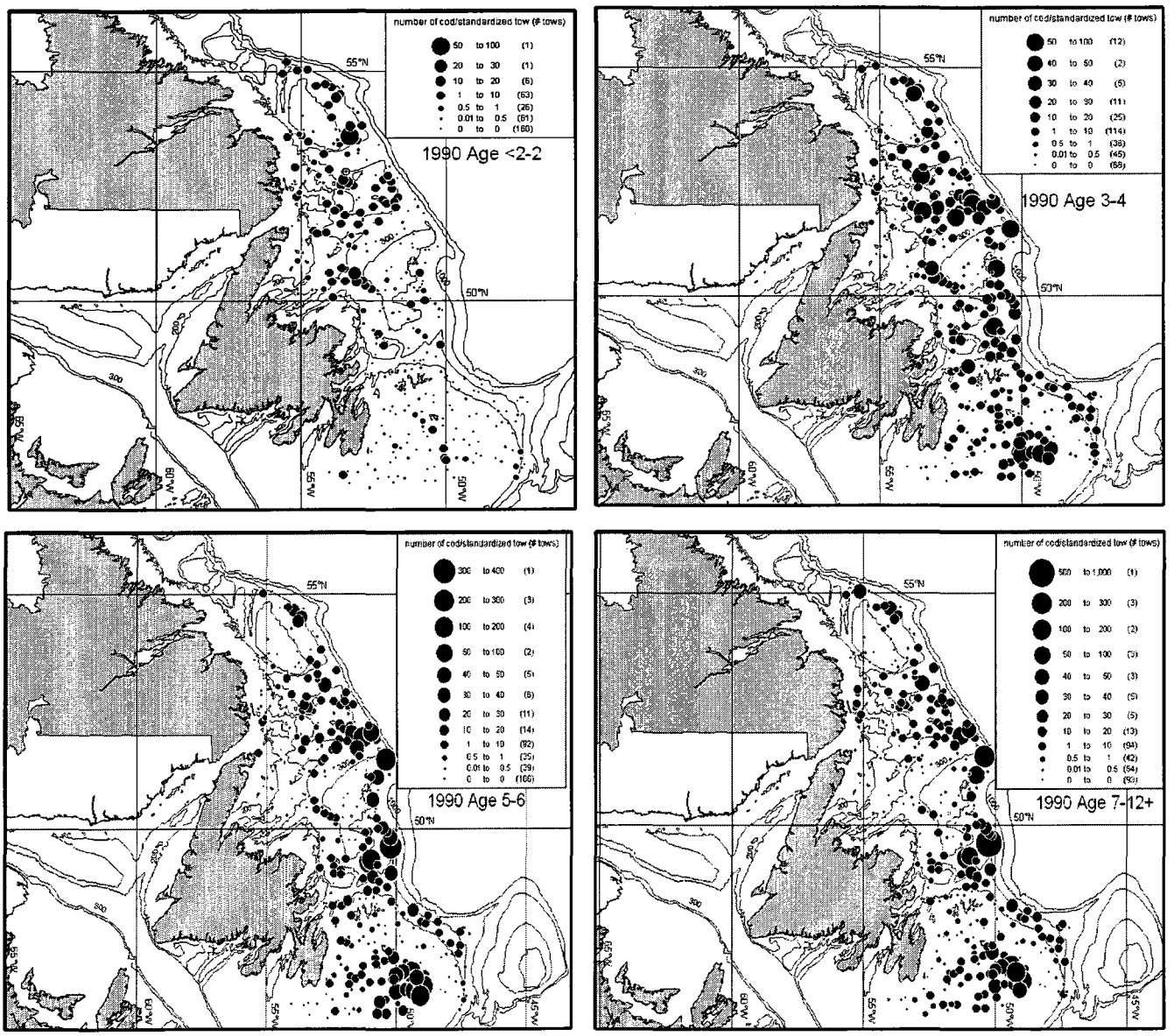

Figure 4.13. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1990.

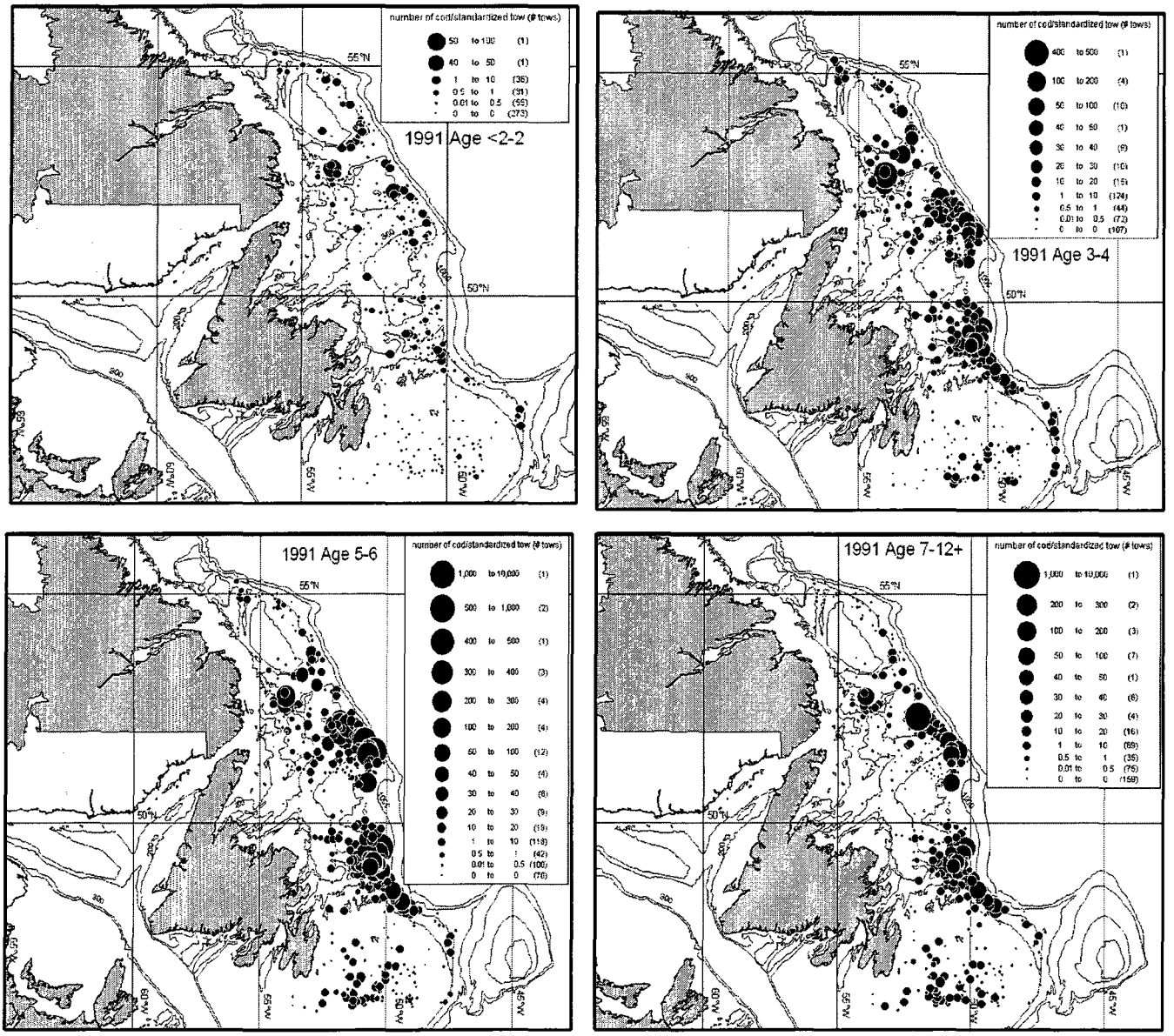

Figure 4.14. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1991.

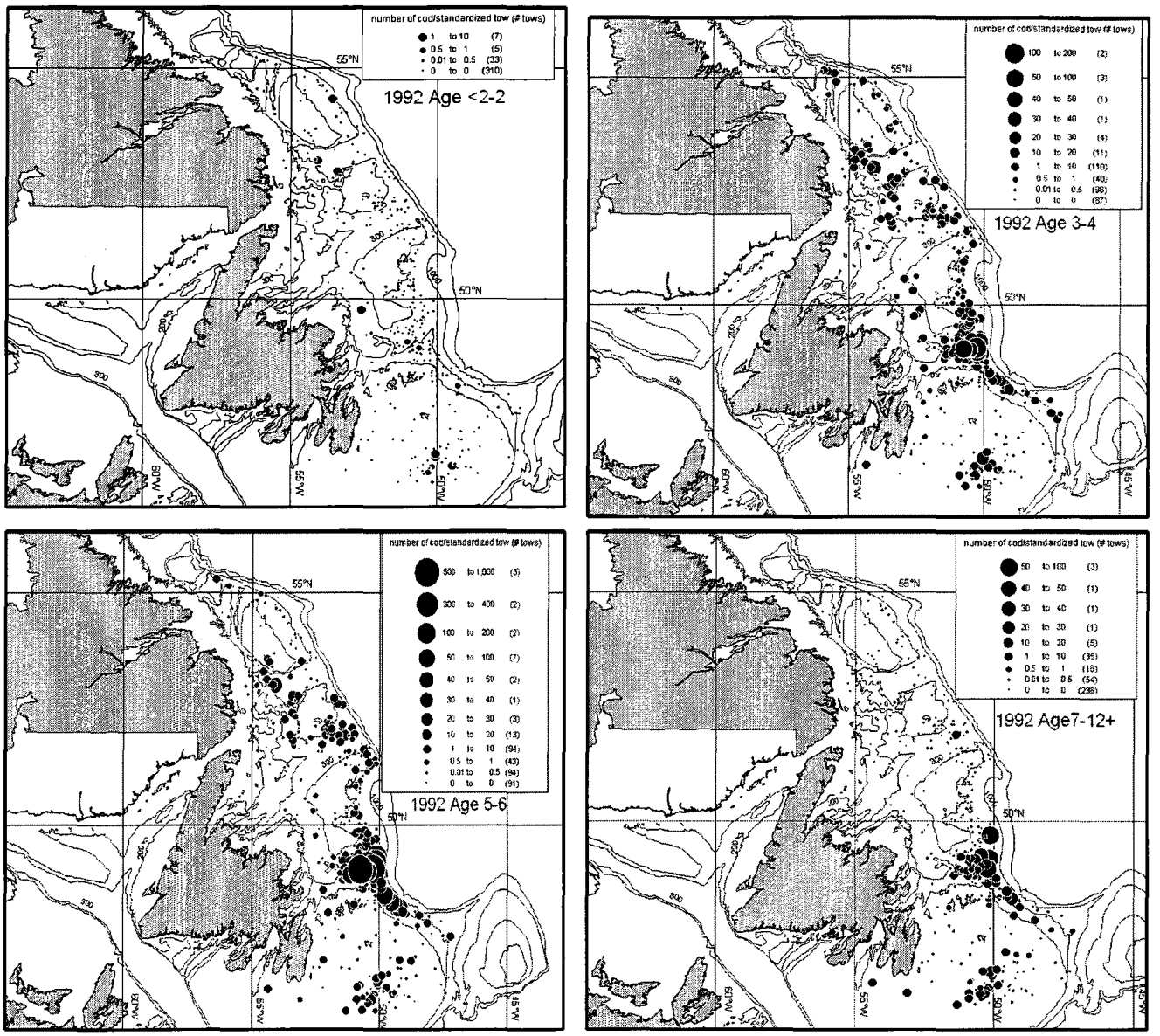

Figure 4.15. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1992.

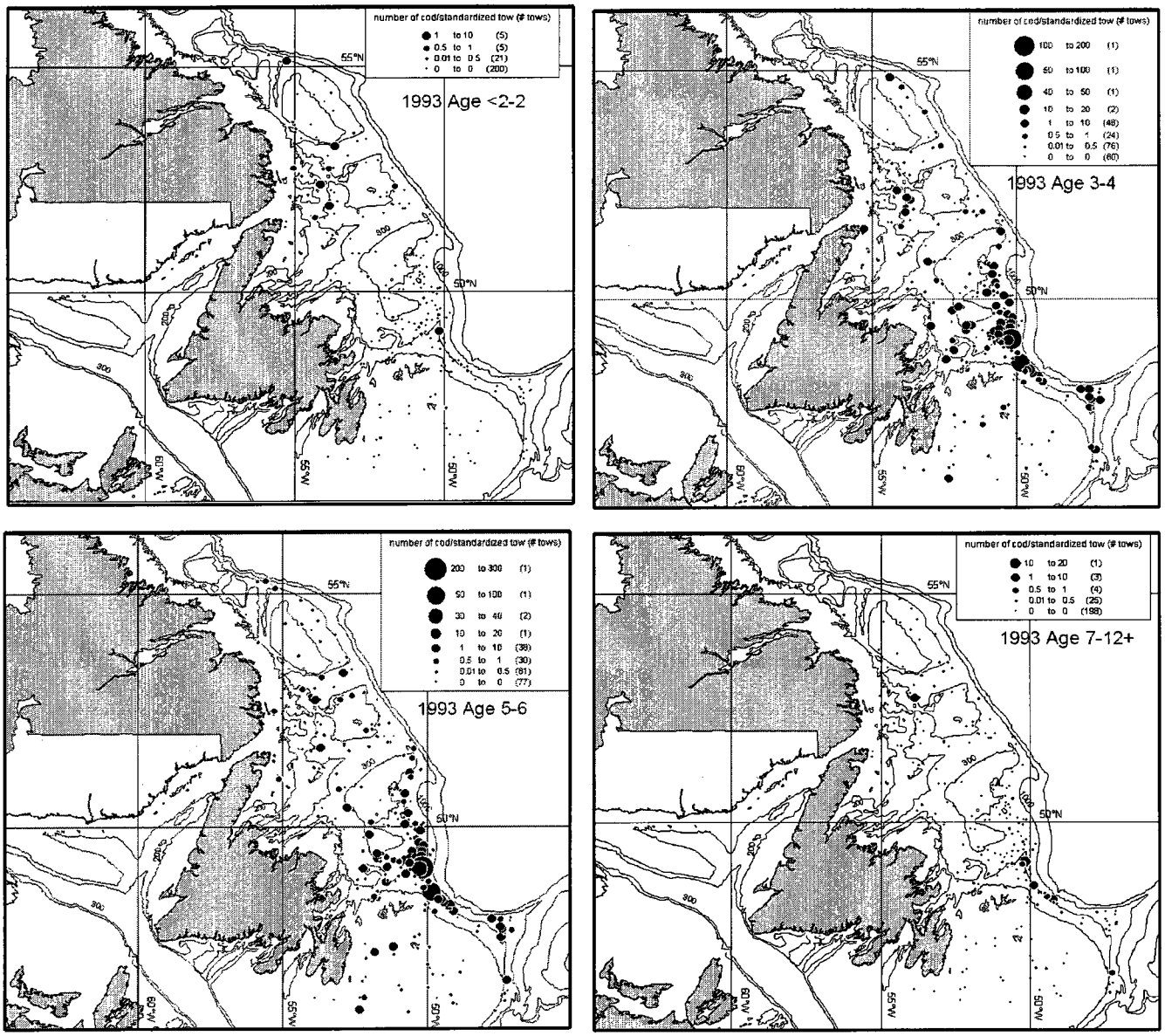

Figure 4.16. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1993.

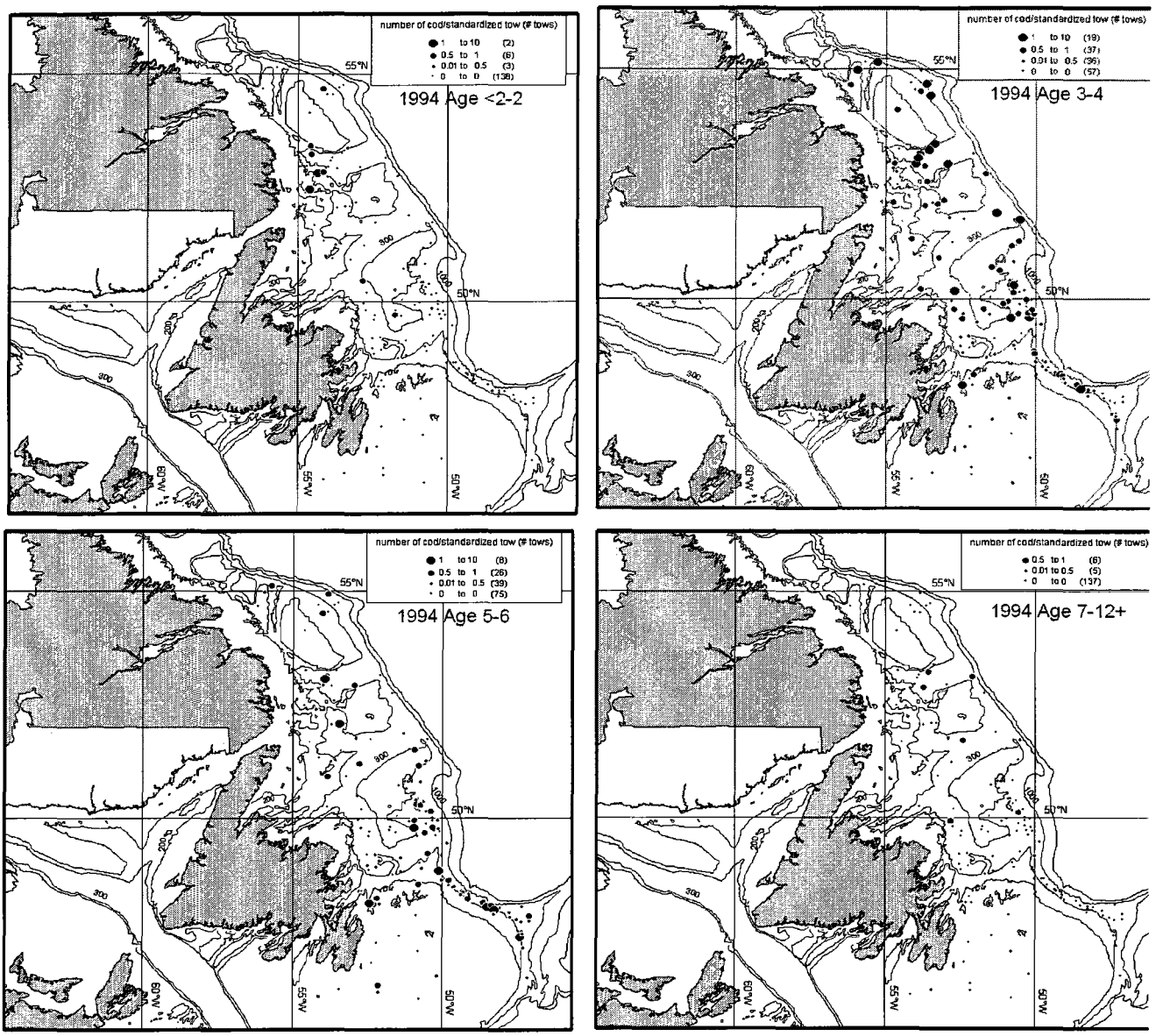

Figure 4.17. Cod distribution in Divisions 2J3KL of 4 age groups, ≤2-2, ages 3-4, ages 5-6, and ages 7-12+ in 1994.

4.1.2 Distributions maps for Divisions 4RS

Cod ages ≤ 2 showed a low abundance throughout 4RS, and were mainly found along the Esquiman Channel, the western coast of Newfoundland and the Quebec North Shore until 1985 when there were almost none in the survey data (Figure 4.24). This low abundance was also evident in 1986 and 1987 (Figure 4.25 and Figure 4.26). In 1988 there were more juveniles caught than in previous years with larger tows along the Esquiman Channel and in the Anticosti Channel and Laurentian Channels (Figure 4.27). In 1988 and 1989 (Figure 4.27 and Figure 4.28) the tows continued to get larger with one large tow near Bay St. George in 1989 (south of the Port au Port Peninsula). In 1990 and 1991 (Figure 4.29 and Figure 4.30) there was a low number of juvenile cod (80 tows with < 30 cod per nautical mile) caught along the Esquiman Channel, these low counts continued to decrease to almost 0 juveniles (70 tows with 0 fish) in 1994 (Figure 4.33).

From 1978 and 1979, cod ages 3-4 years old were distributed along the Esquiman Channel (Figure 4.18 to 4.19). In 1980 (Figure 4.20) cod aggregated near Bay St. George, Port au Port Peninsula with tows of 100 -200 cod per nautical mile. In 1983 (Figure 4.22), this age group showed a higher abundance throughout 4RS with signs of aggregation along the Esquiman Channel approximately near latitude 50N with tows of 200 up to 300 cod per nautical mile. In 1984 (Figure 4.23) cod remained distributed along the Esquiman Channel with a large tow of 500 up to 1000 cod per nautical mile and in 1985 there were a few tows (100-200 cod per nautical mile) along the northern part of Esquiman Channel. The distribution shifted south in 1986 (Figure 4.25), and became aggregated near Bay St. George. In 1987 (Figure 4.26) cod ages 3-4 formed small

aggregations along the Esquiman Channel off of Bay St. George, Port au Port Peninsula with tows of 100 up to 200 cod per nautical mile. In 1988 (Figure 4.27) the distribution was spread out throughout the Esquiman Channel (east of Anticosti Island). This distribution remained the same until 1990 when the distribution became more spread out from the Esquiman Channel to Laurentian Channel with an aggregation off of the Port au Port Peninsula with tows of up to 200 cod per nautical mile. From 1991 to 1994 (Figure 4.30 to 4.33) the distribution shifted and became concentrated along the Esquiman Channel, with aggregations forming from the Bay St. George (Port au Port Peninsula) to Port aux Basques. These areas became geographically fixed locations for aggregations in the early 1990s (Figures 4.30-4.33).

Cod ages 5-6 were distributed along the Esquiman Channel in 1978 (Figure 4.18) and started to show signs of aggregation off the western point of the Port au Port Peninsula and near the Straits of Belle Isle with tows of up to 500 cod per nautical mile. In 1979 the cod abundance declined (Figure 4.19) and in 1980 (Figure 20) the northern Gulf cod became aggregated again off the western point of the Port au Port Peninsula with tows of 200-300 cod per nautical mile. In 1981 (Figure 4.21) the cod aggregated off of Port au Basques near the Cabot Strait with high counts of 200 up to 400 cod per nautical mile. In 1983 and 1984 (Figure 4.22 and Figure 4.23) ages 5-6 showed higher counts (1000 + cod per nautical mile) with signs of aggregation along the Esquiman Channel specifically north of the Port au Port Peninsula (approximately near longitude 59° N). In 1985 (figure 4.24) the northern Gulf cod are distributed throughout the Esquiman Channel with signs of aggregation east of Anticosti Island. In 1986 (Figure 4.25) cod ages 5-6 formed a large aggregation off the western point of the Port au Port

Peninsula with large tows of 1000 up to 10,000 cod per nautical mile. These aggregations started to shrink in 1987 (Figure 4.26) with lower counts (< 30 cod per nautical mile) throughout the Esquiman Channel. From 1988 to 1989 (Figure 4.27 to Figure 4.28) there were lower counts of cod ages 5-6 throughout the Esquiman Channel and the Cabot Strait. Gulf cod were distributed along the Esquiman Channel and west of Anticosti Island in 1989 and again became aggregated off of Bay St. George (Port au Port Peninsula) and Port aux Basques in 1990 (Figure 4.29). An aggregation formed in 1991 (Figure 4.30) in a fixed location between the Port au Port Peninsula and Port aux Basques and this pattern persisted until 1994 (Figure 4.33).

Cod ages 7-12+ aggregated off of the western point of the Port au Port Peninsula in 1978, and distribution spread throughout the Esquiman Channel in 1979 (Figure 4.19). There was a larger aggregation off Bay St. George between Port aux Basques and Port au Port Peninsula in 1980 with tows of up to 300 cod per nautical mile. In 1981 (Figure 4.21) the Gulf cod aggregated off of Port aux Basques, near the Cabot Strait with counts of up to 400 cod per nautical mile. In 1983 and 1984 (Figure 4.22 and Figure 4.23) the abundance of Gulf cod ages 7-12+ increased (tows more than 1000 cod per nautical mile) and they were distributed throughout much of 4RS. In 1985 (Figure 4.24) aggregations of cod started to form along the Esquiman Channel, and in 1986 (Figure 4.25) these older cod were aggregated off the Port au Port Peninsula and Bay St. George. The extent of this aggregation and overall abundance contracted in 1987 (Figure 4.26) and even more in 1988 (Figure 4.27), with low abundance throughout 4RS. In 1989 (Figure 4.28) the abundance increased slightly with tows with high counts (500 up to 1000 cod per nautical mile) concentrated off of Port aux Basques. This pattern of aggregation off of Port aux

Basques along the Cabot Strait continued in 1990 (Figure 4.29). Then in 1991 large aggregations formed, which shrank in size up to 1994 (Figure 4.33). The wide range of changes in the distribution of the northern Gulf cod could be attributed to the variability of ice coverage in the northern Gulf. The research survey of the northern Gulf cod was vulnerable to these changes in ice cover, which in turn affected the areas sampled (Castonguay *et al.* 1999)

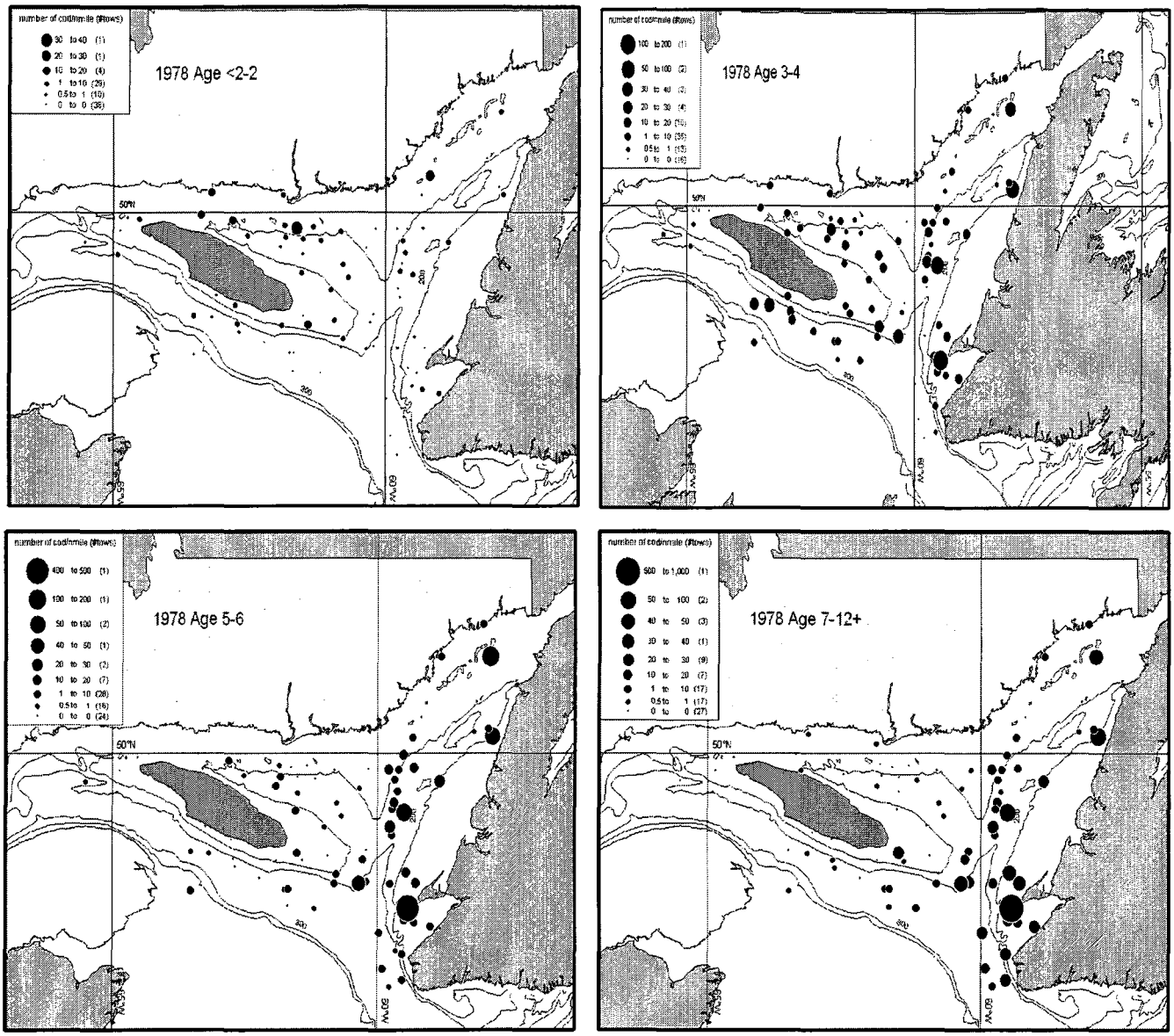

Figure 4.18. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1978.

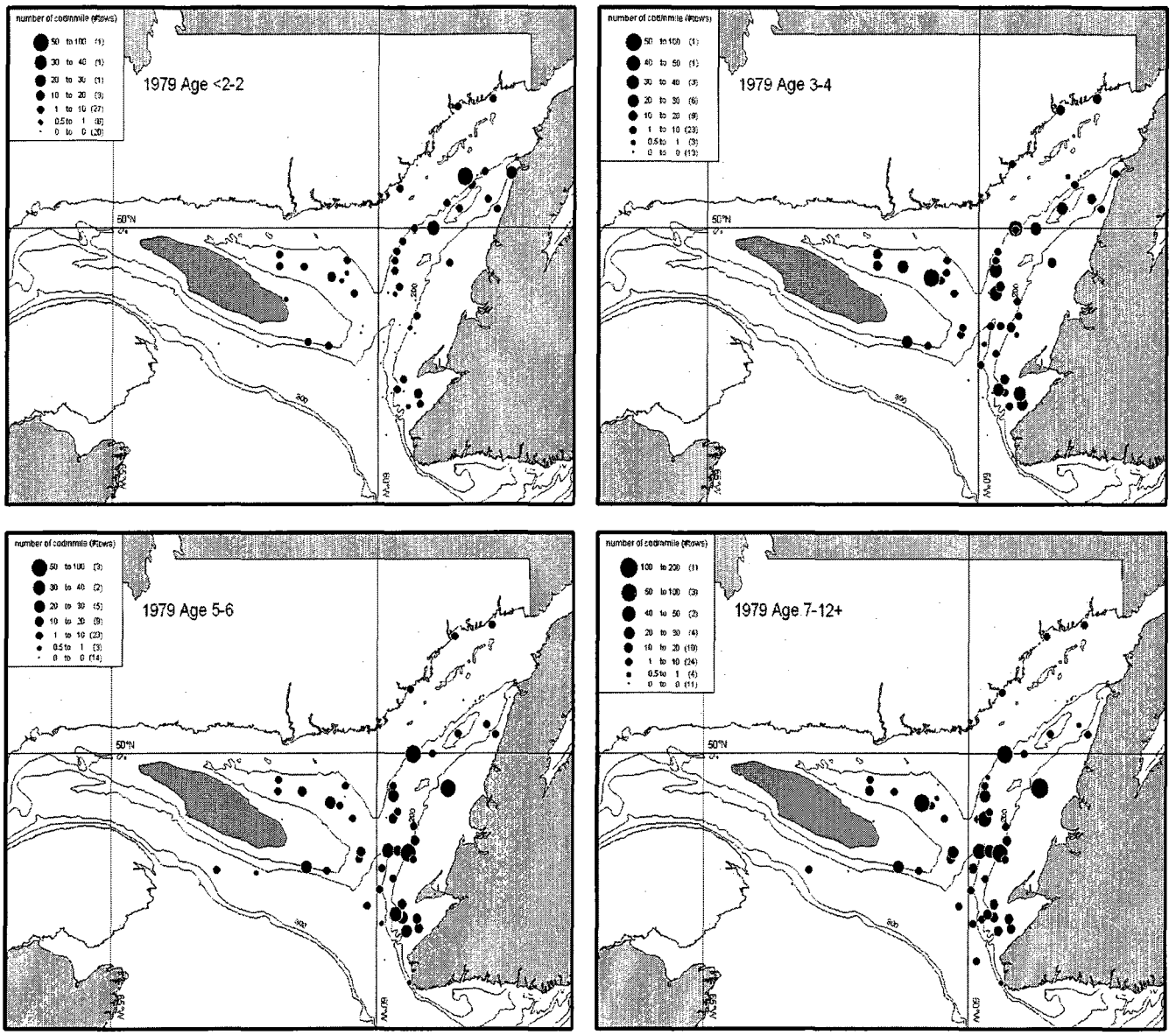

Figure 4.19. Cod distribution in Divisions 4RS of 4 age groups≤ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1979.

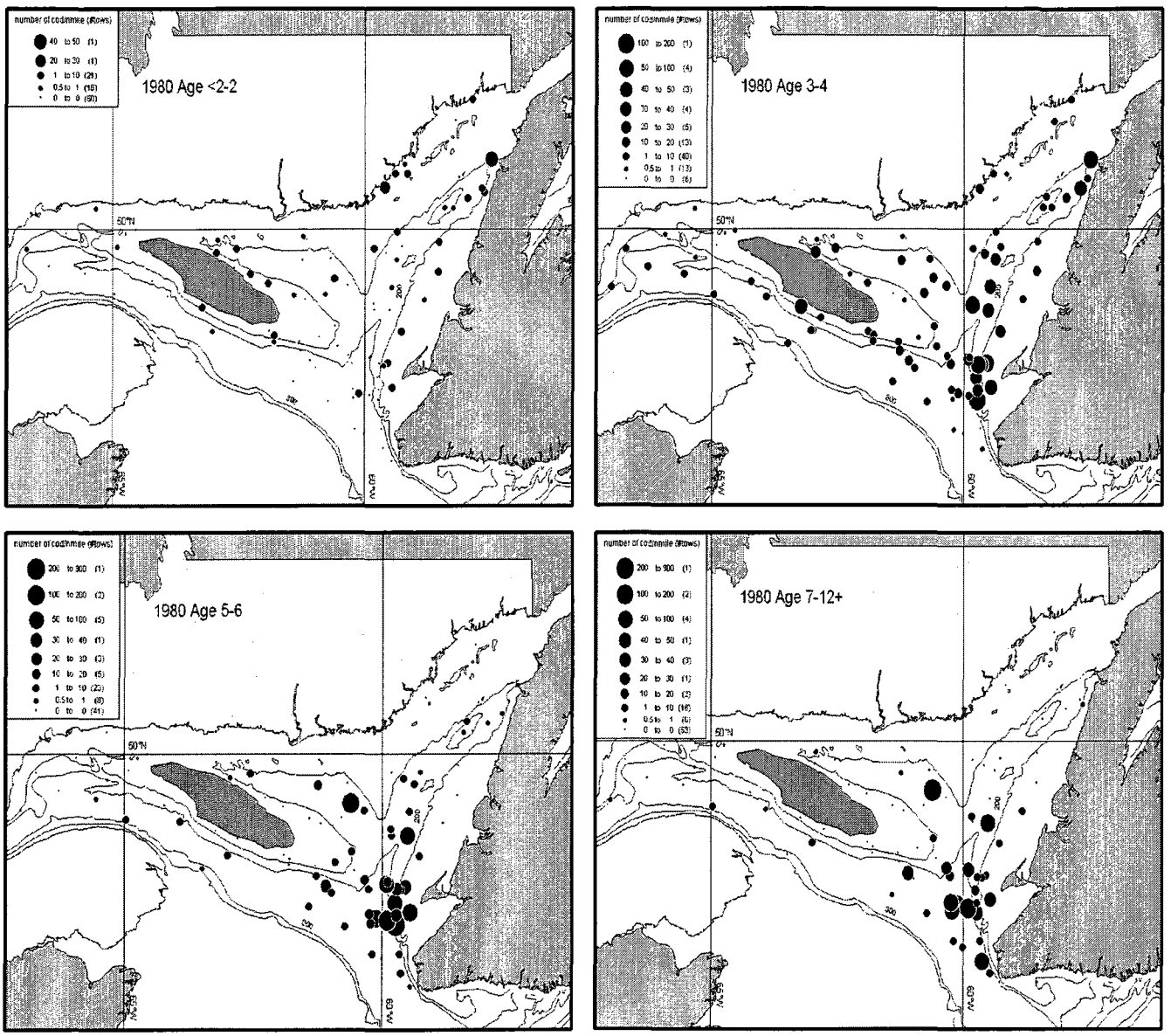

Figure 4.20. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1980.

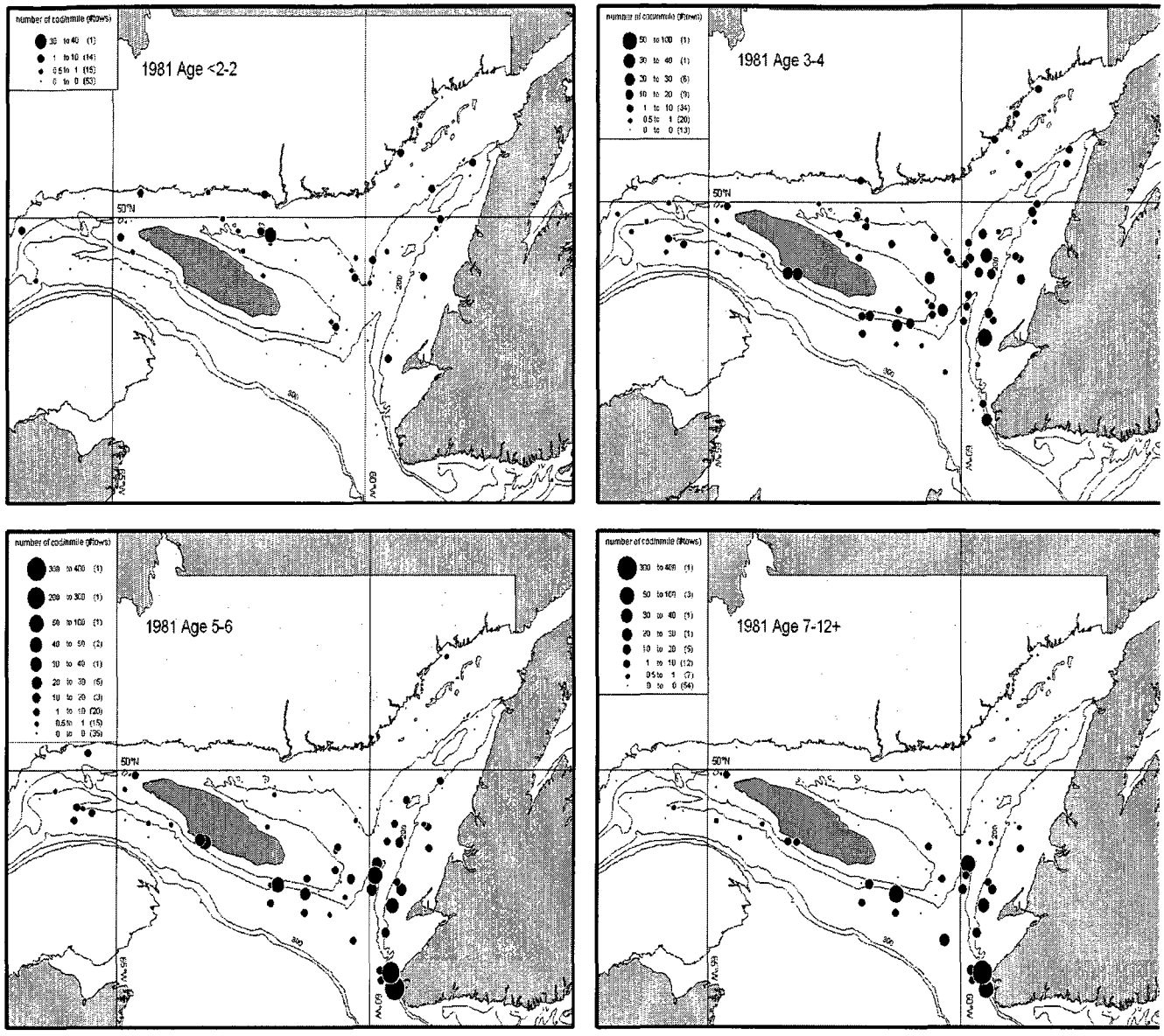

Figure 4.21. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1981.

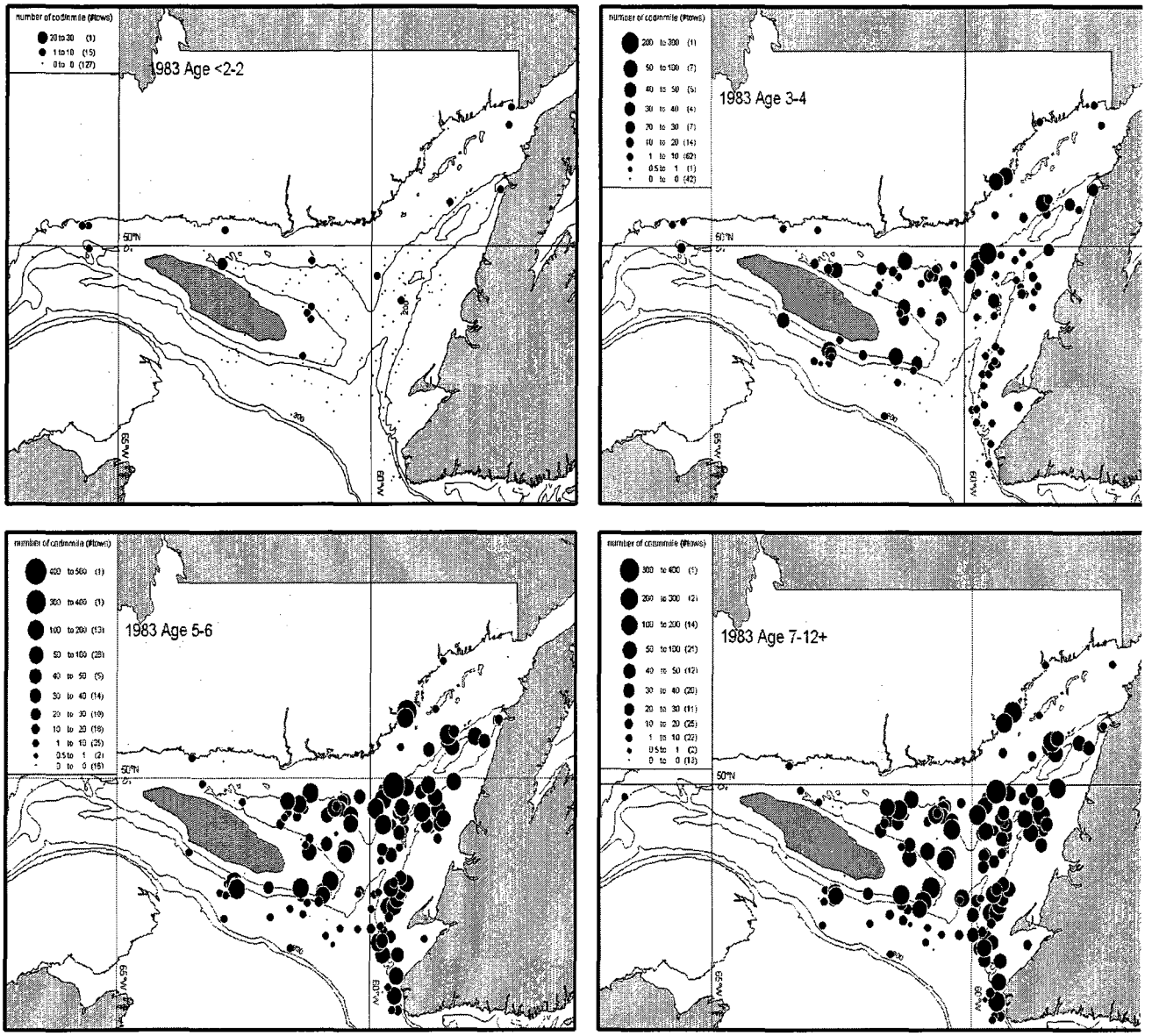

Figure 4.22. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1983.

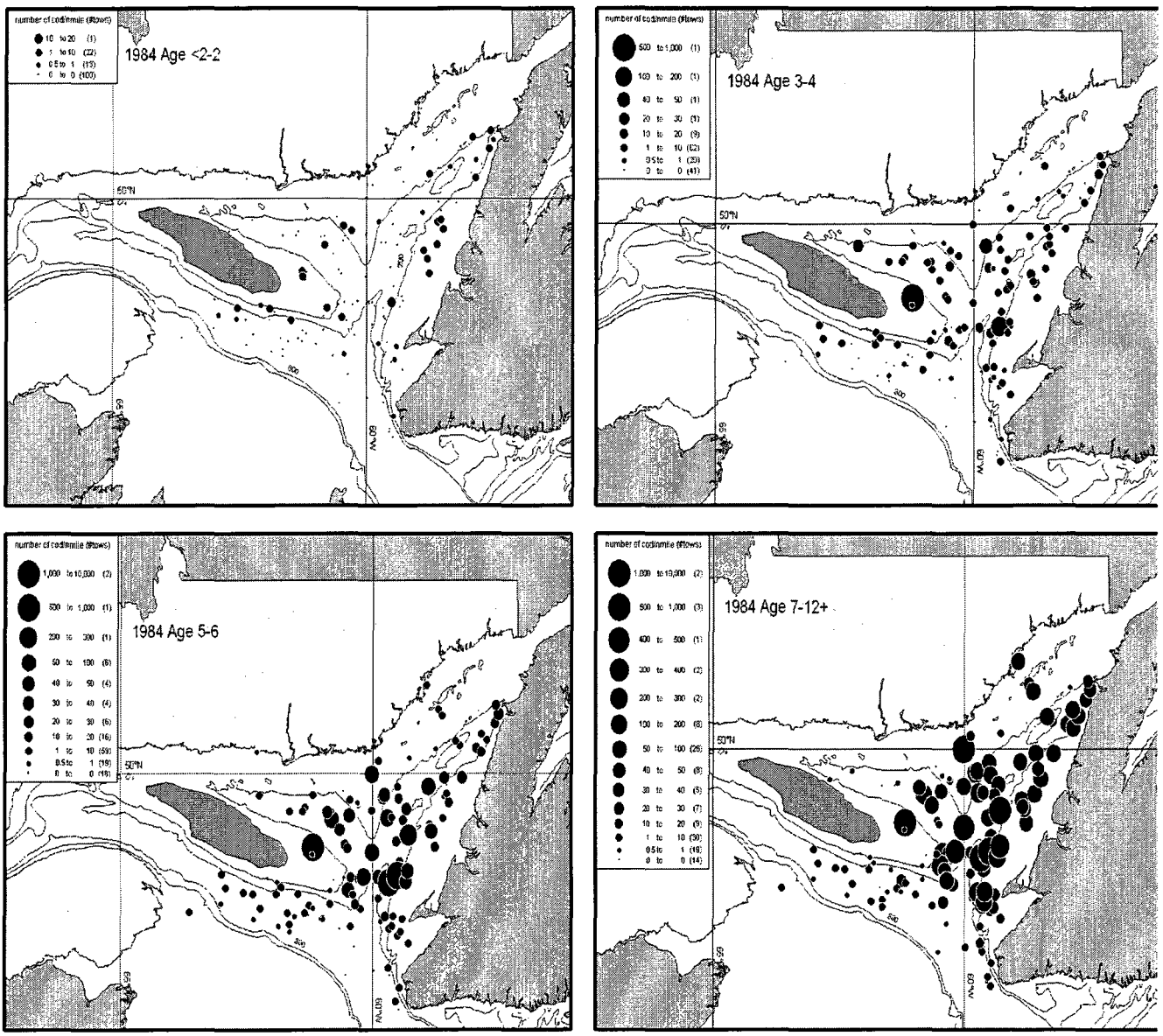

Figure 4.23. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1984.

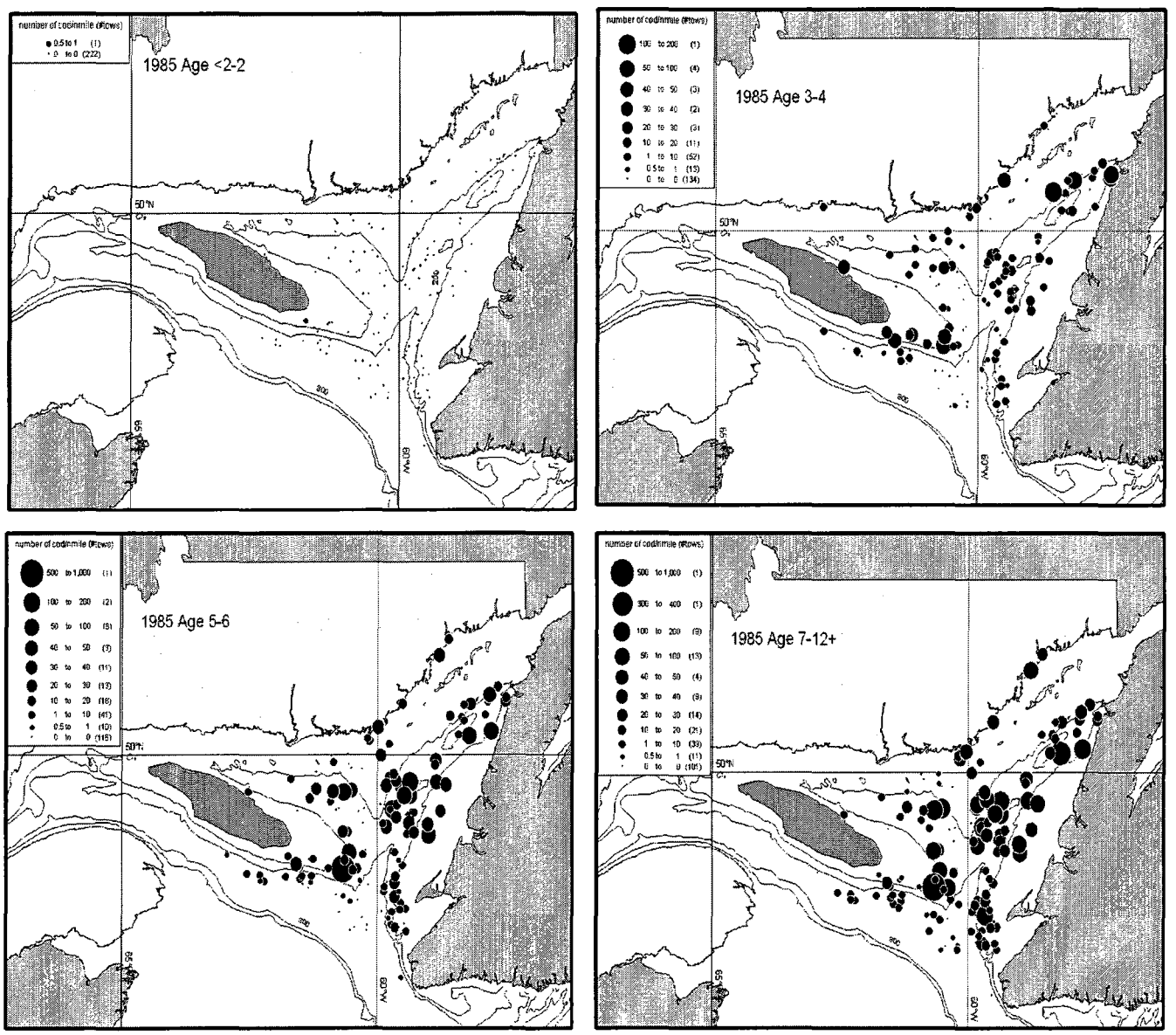

Figure 4.24. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1985.

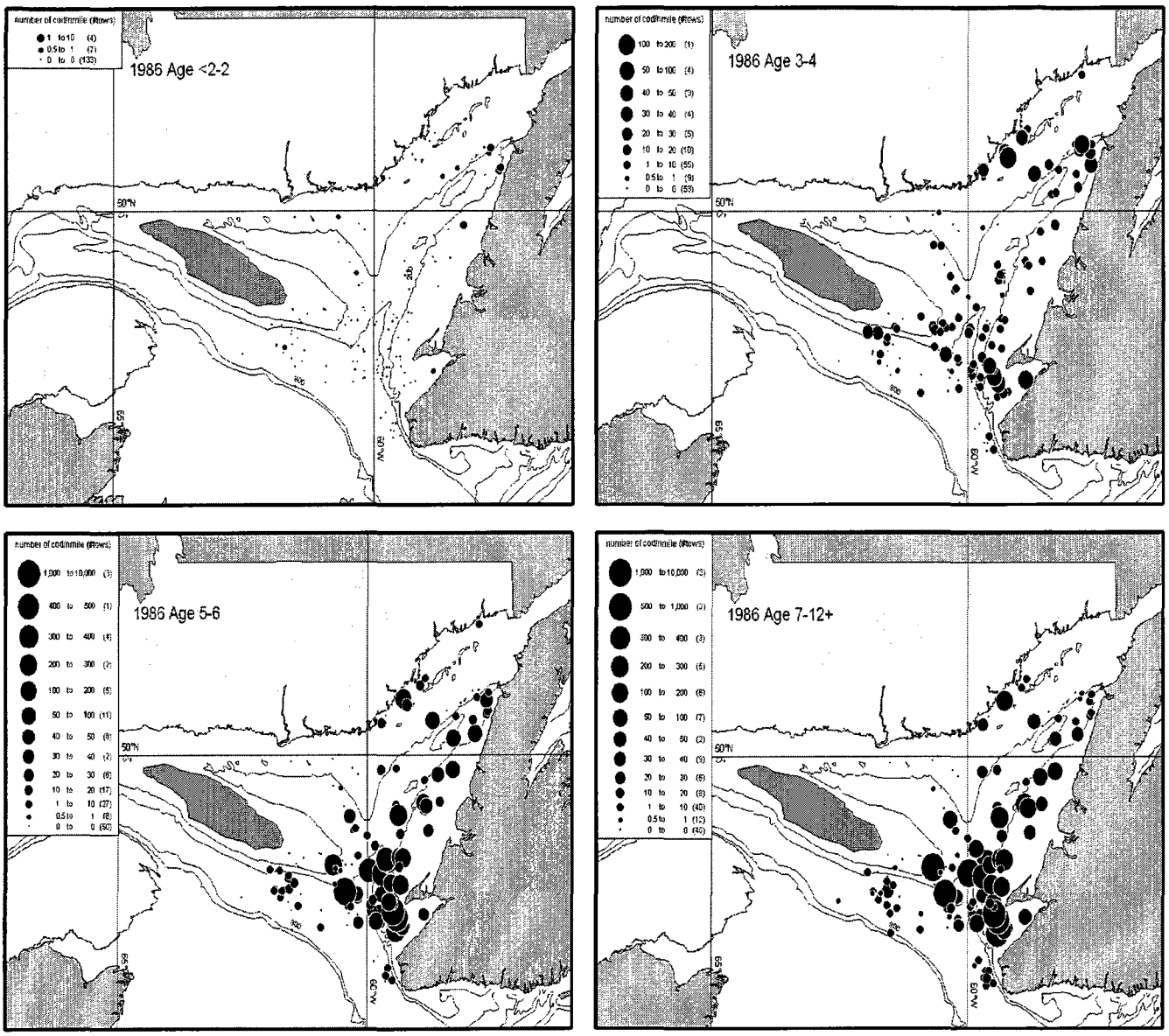

Figure 4.25. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1986.

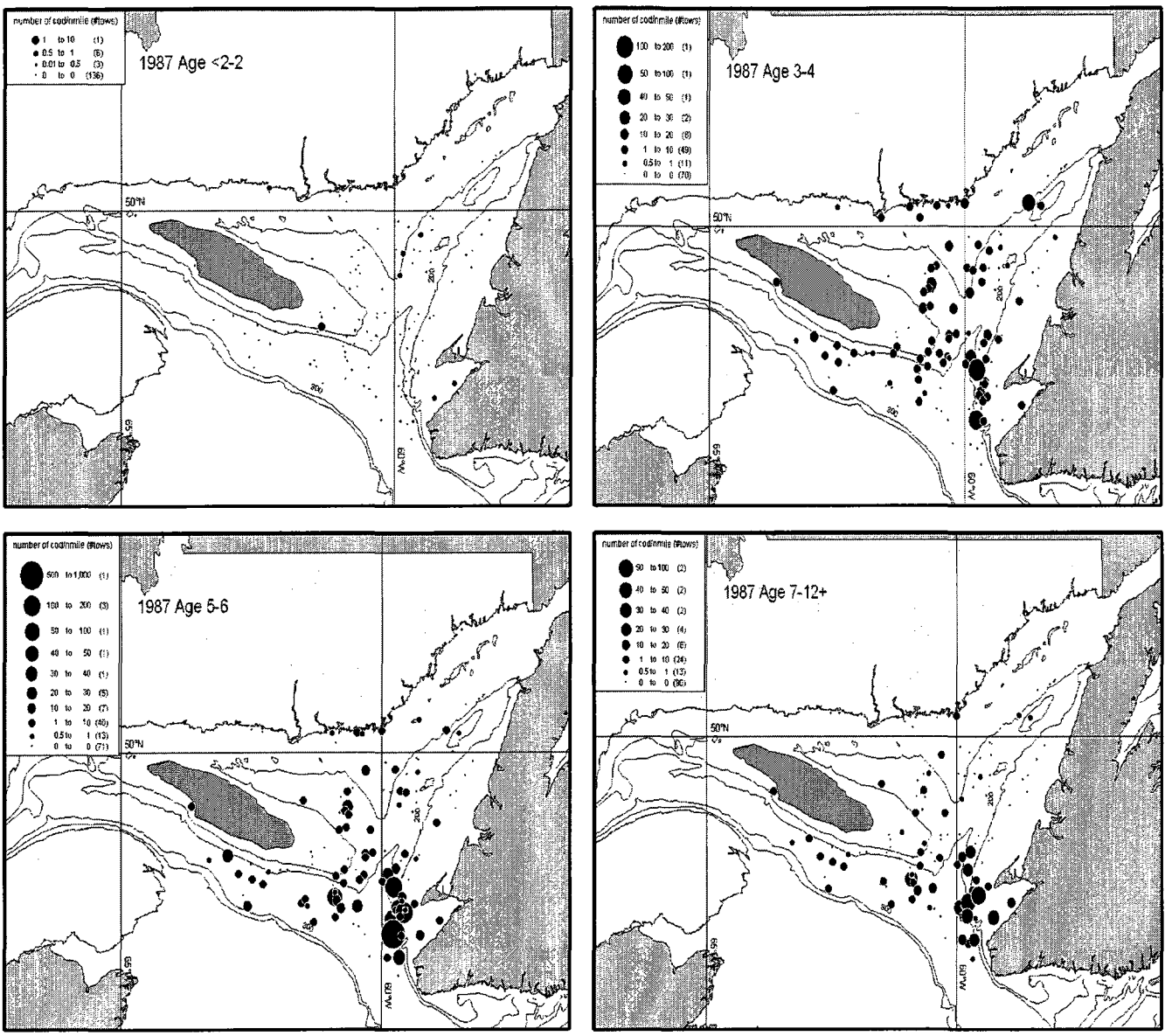

Figure 4.26. Cod distribution in Divisions 4RS of 4 age groups ≤ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1987.

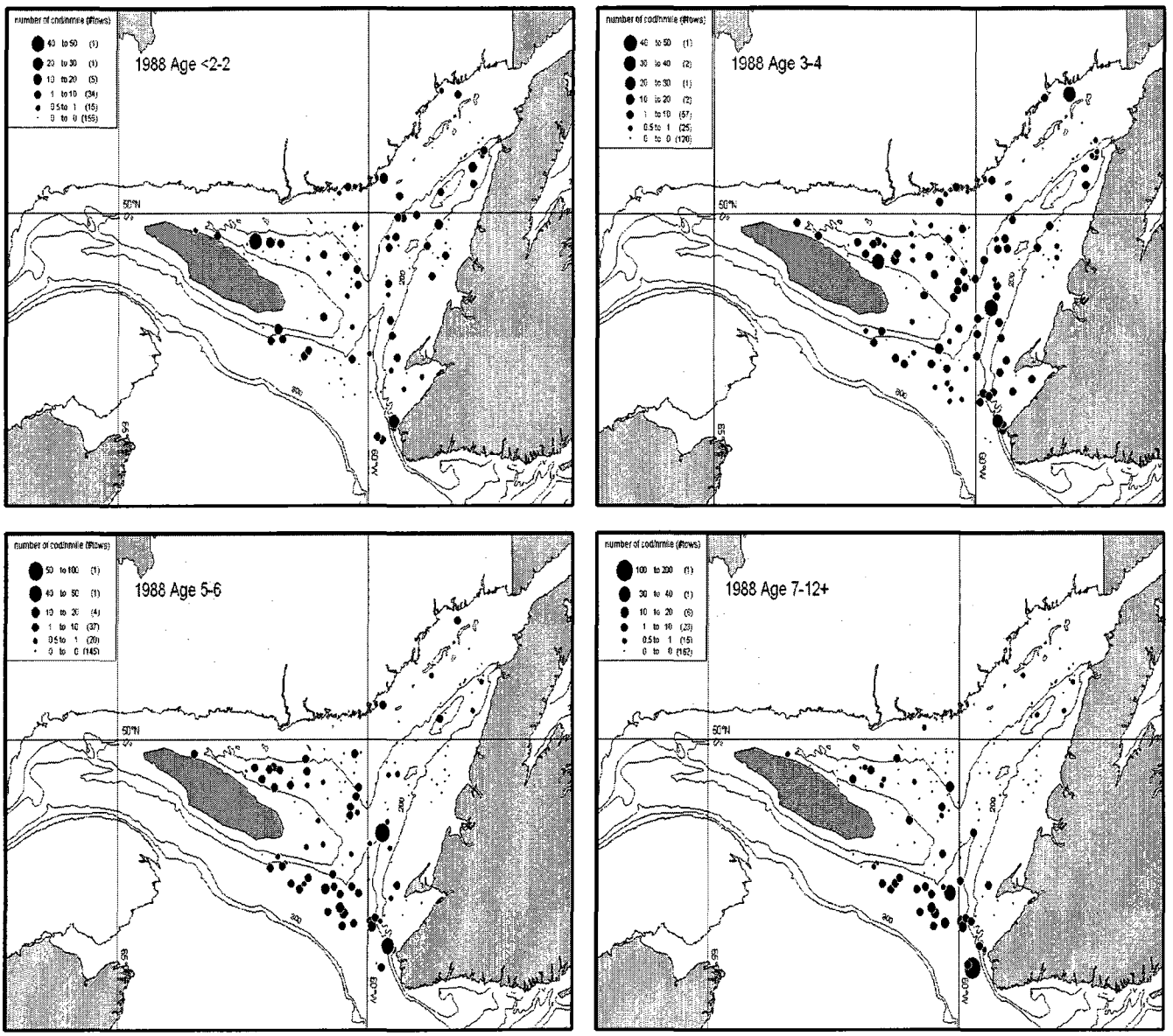

Figure 4.27. Cod distribution in Divisions 4RS of 4 age groups ≤ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1988.

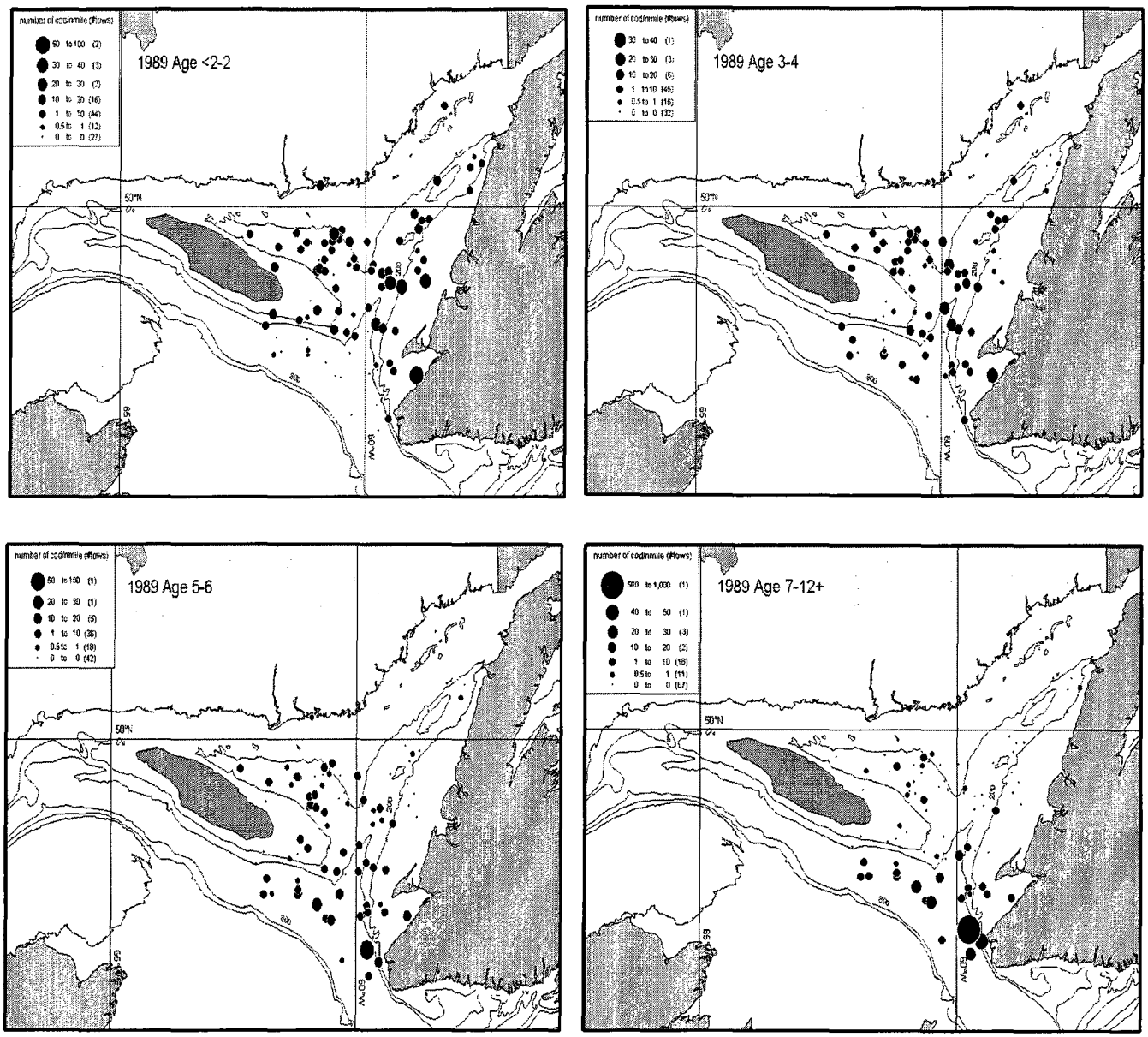

Figure 4.28. Cod distribution in Divisions 4RS of 4 age groups ≤ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1989.

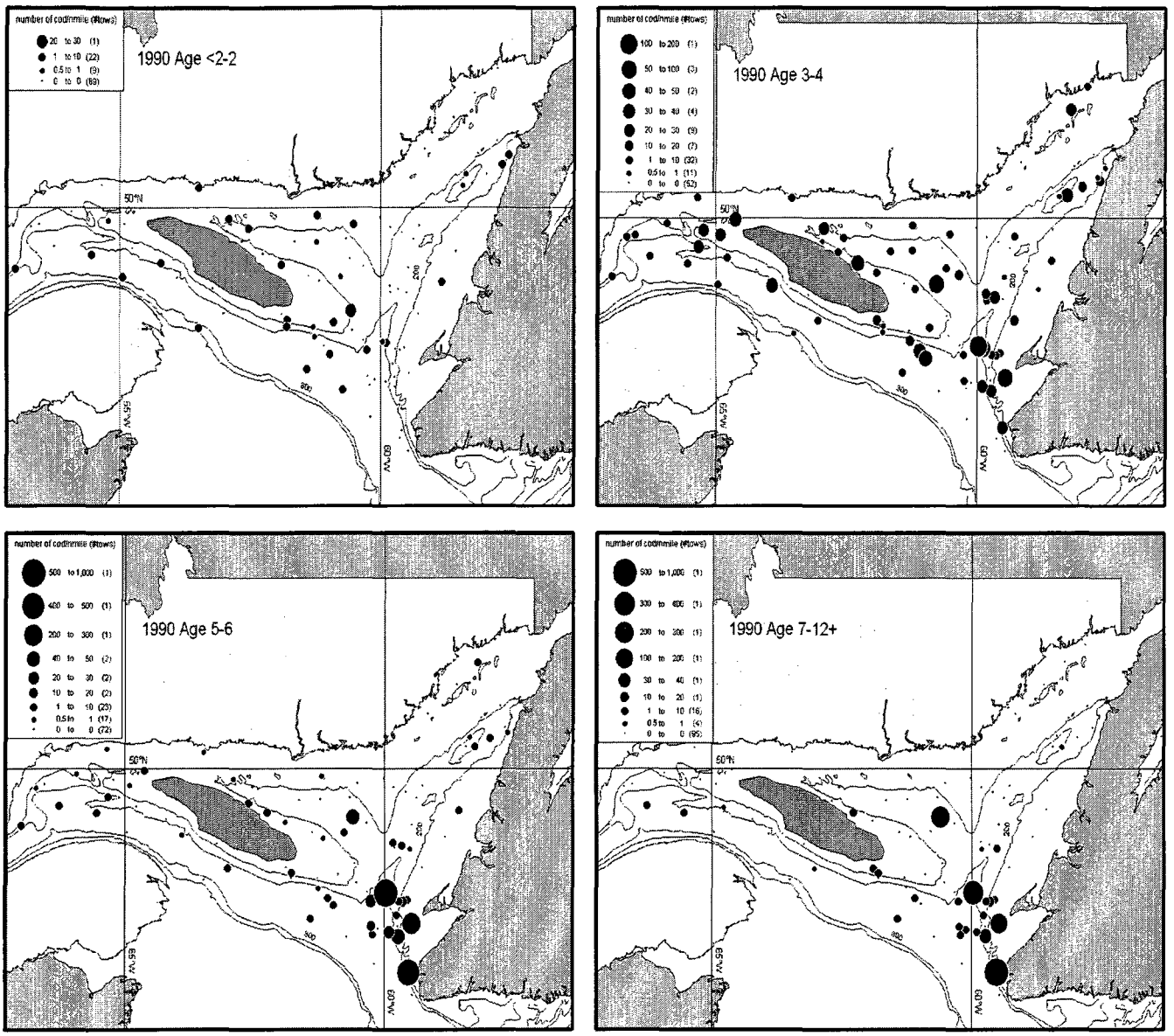

Figure 4.29. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1990.

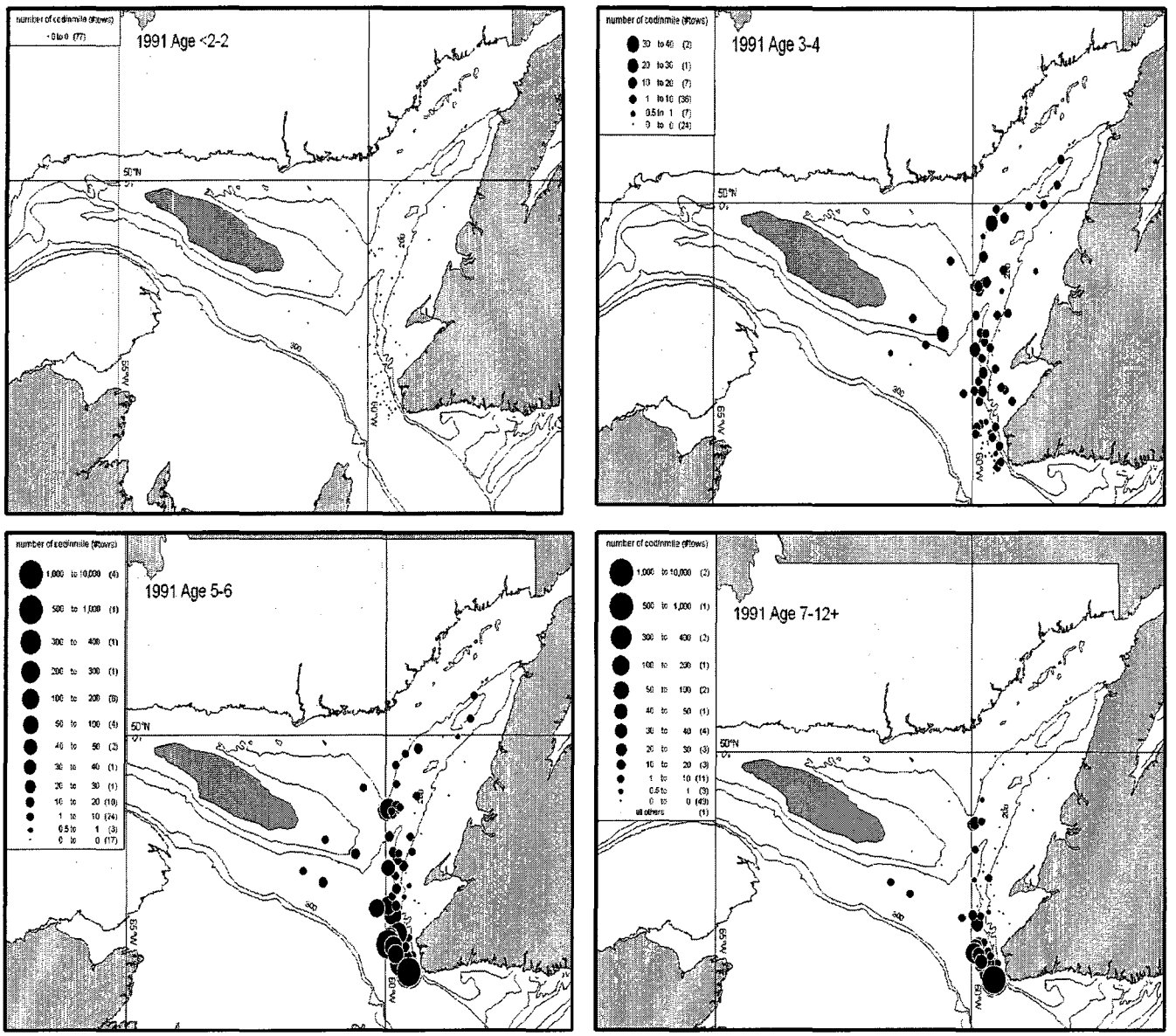

Figure 4.30. Cod distribution in Divisions 4RS of 4 age groups ≤ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1991.

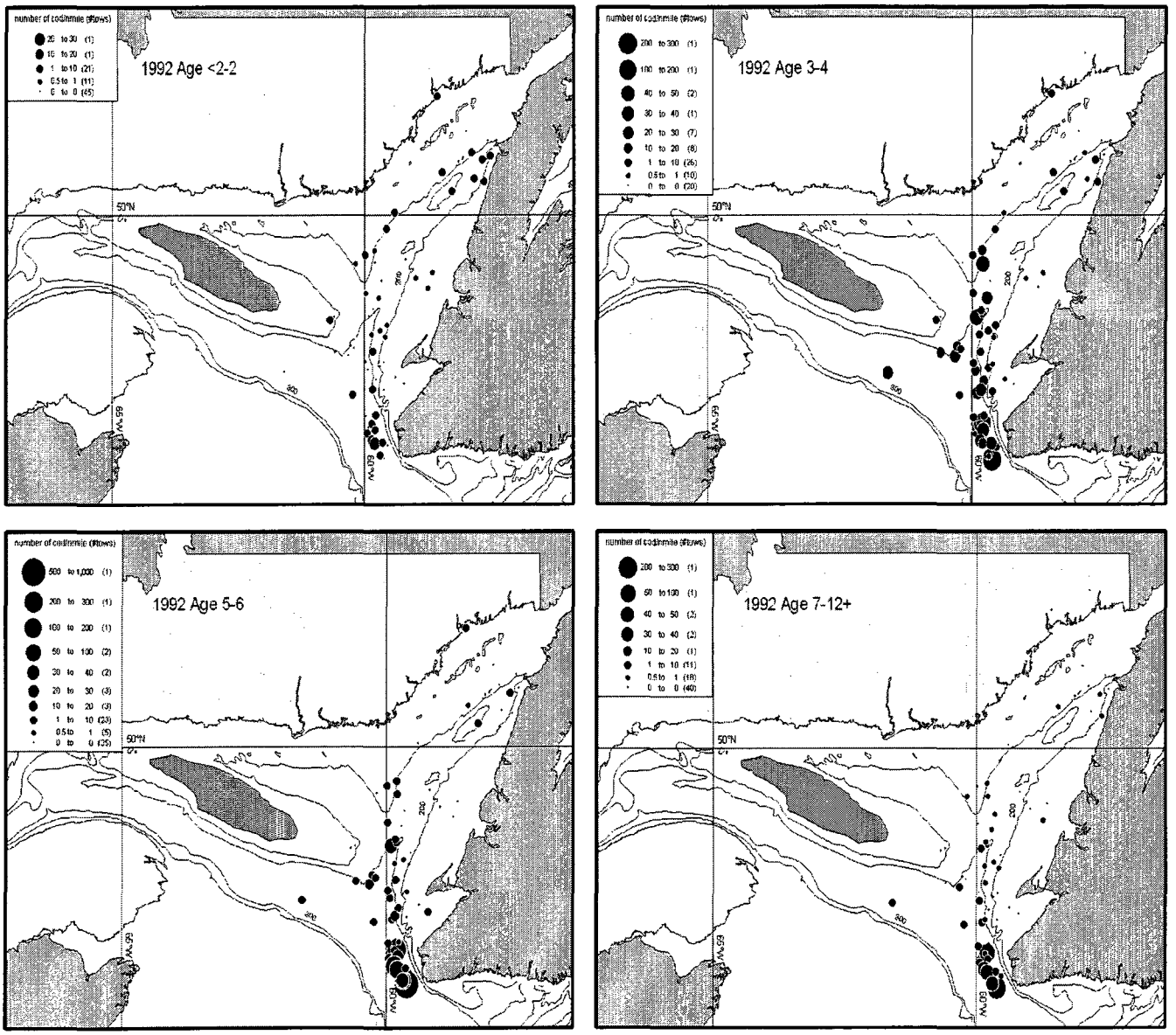

Figure 4.31. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1992.

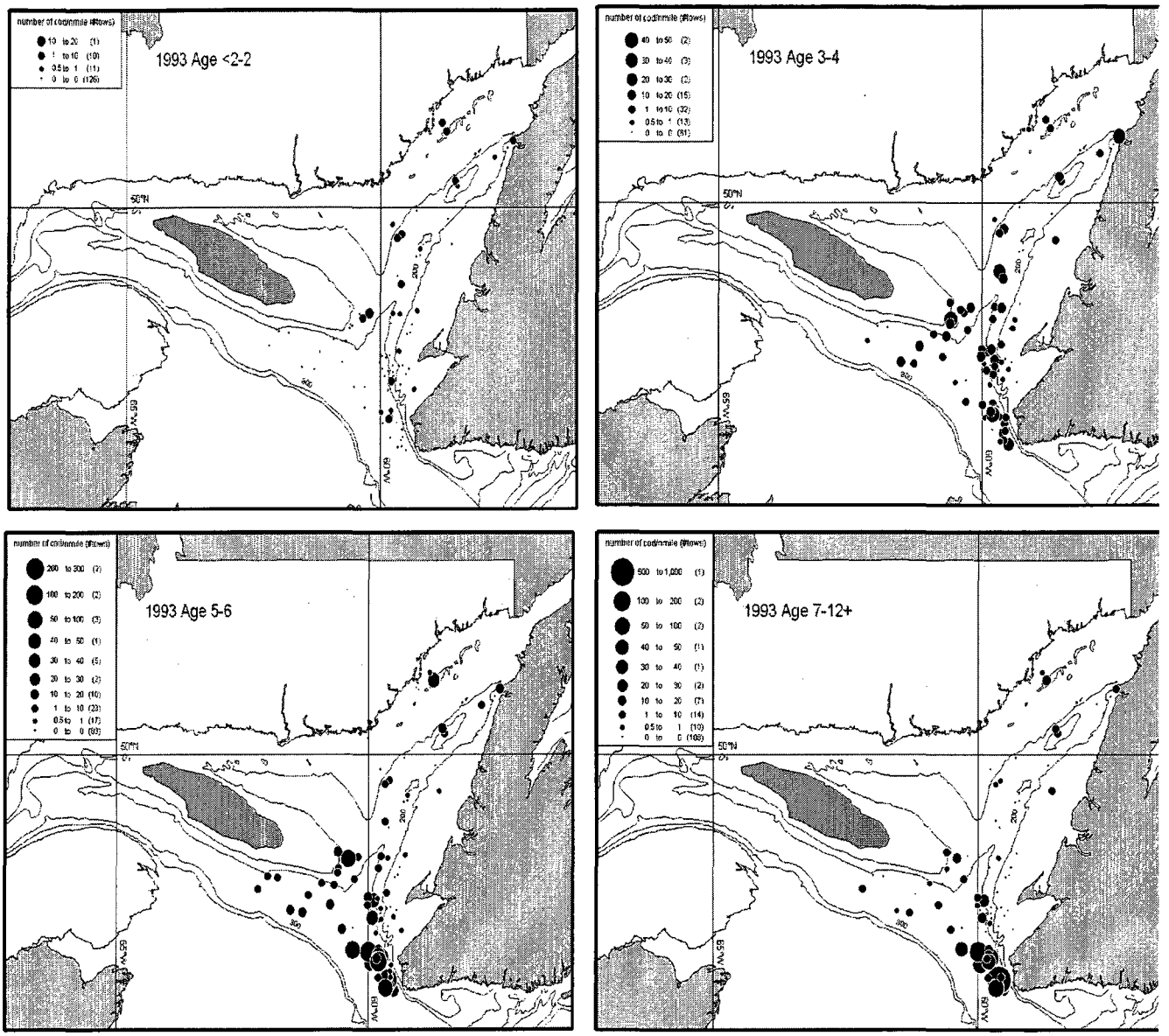

Figure 4.32. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1993.

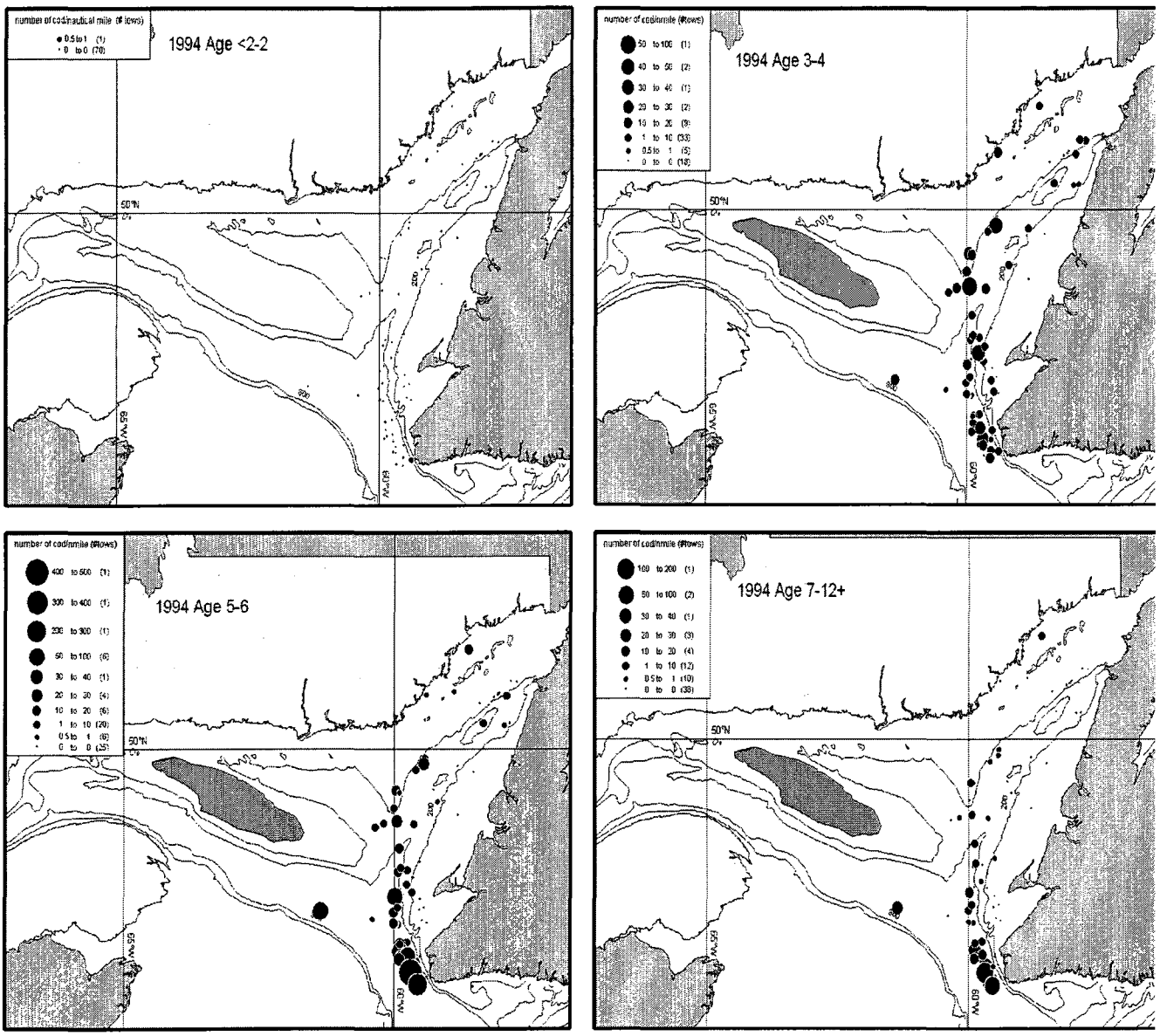

Figure 4.33. Cod distribution in Divisions 4RS of 4 age groups $\leq$ 2, ages 3-4, ages 5-6 and ages 7-12+ in 1994.

4.2 Gini Index

4.2.1 Divisions 2J3KL

As cod become more aggregated the Lorenz curve bends downwards (Figure 4.34) to the right within the unit square as the Gini Index increases. If cod were equally distributed among tow locations the Lorenz curve would be the dotted line (identity function). Figure 4.34 indicates that the Gini Index (degree of aggregation) for cod ages 7-12 increased from 58% in 1983 to 94% (highly aggregated) in 1992 in NAFO Divisions 2J3KL.

The Gini Index increased for all 4 age groups (ages $\leq$2; ages 3-4; ages 5-6 and ages 7-12+) over time (1981-1994) (Figure 4.35) but to different degrees. Cod ages 7-12+ (spawner biomass) showed the most prominent increase in aggregation (Figure 4.35) compared to the other three age groups. The Gini index increased from 70% in the early 1980s to over 95% in the early 1990s, starting after 1984. This is consistent with Myers and Cadigan's findings (1995) showing the same increase in aggregation in the early 1990s for older cod (ages 7+) (Myers and Cadigan 1995). Ages 5-6 also displayed an increase in aggregation (from 70% to 90%) but not as strongly as ages 7-12+. For the Atlantic cod ages 3-4 the Gini index increased from 70% in the early 1980s to over 80% in the early 1990s.

The juveniles (ages $\leq$2) did not show as strong a change in aggregation as was shown in the older cod (ages 7-12+) from 1981-1994 (Figure 4.35). In the early 1980s the Gini index started at approximately 80% in juveniles, compared to at 70% in the other three age groups. This could be a result of habitat selective behavior, as the juveniles tend

to remain inshore in shoals and bays. Dalley and Anderson (1997) found that an ontogenetic pattern of distribution existed whereby age 0 fish were distributed almost exclusively in the inshore, age 1 fish extended further onto shelf areas, and larger juvenile cod (age 2-3) were widely distributed on the shelf. They concluded that as age increased, there was a logarithmic decrease in the ratio of mean catch rate inshore compared with offshore (Dalley and Anderson 1997).

The Gini index was calculated for divisions 2J3K from 1978 to 1994. The survey in 3L did not start until 1981 therefore this division was not used in this time series. The research survey that covered divisions 2J3KL runs a time series in this data set from 1981 to 1994. The Gini index for cod ages 7-12+, along with that for juveniles (Figure 4.36) displayed similar patterns to those shown in (Figure 4.35) Divisions 2J3KL 81-94. However, the Gini index for ages 3-4 and 5-6 decreased in the mid 1980s instead of increasing as in Figure 4.35. This is consistent with the observation that these age groups aggregated in divisions 3L in the early 1990s. Appendix A shows the Gini index for cod ages $\leq$2 to ages 12+ from 1978 to 1994 within each division (2J, 3K, 3L, 4R and 4S).

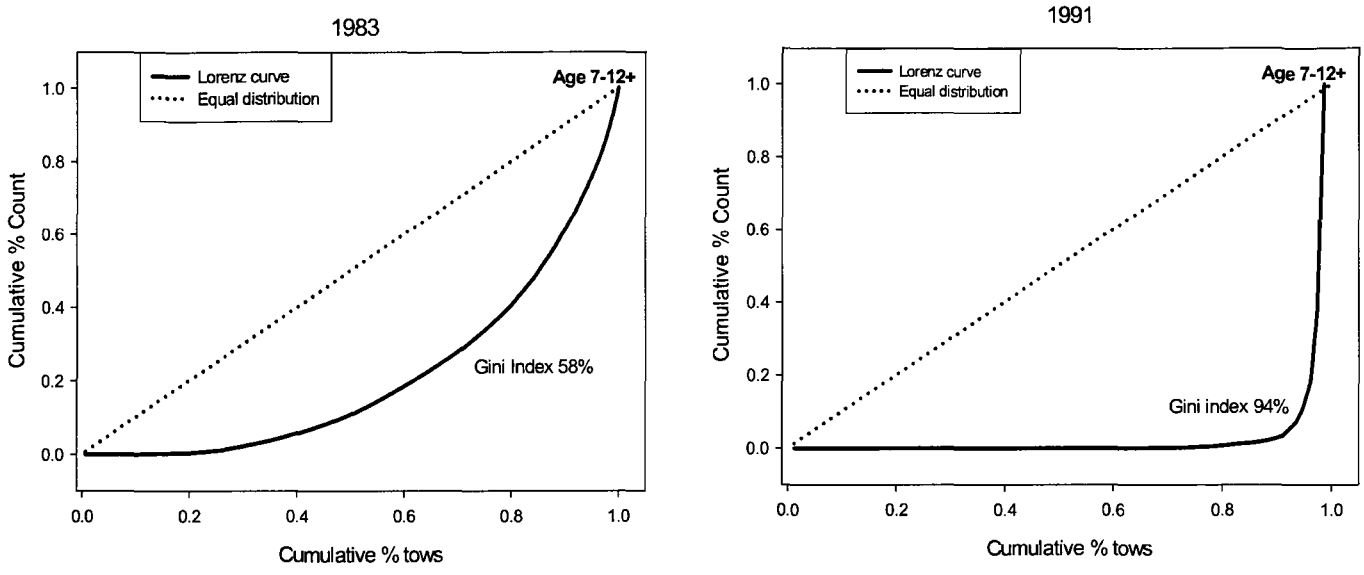

Figure 4.34. Lorenz curve diagrams for NAFO Divisions 2J3KL Age 7-12+ cod aggregation for 1983 and 1991.

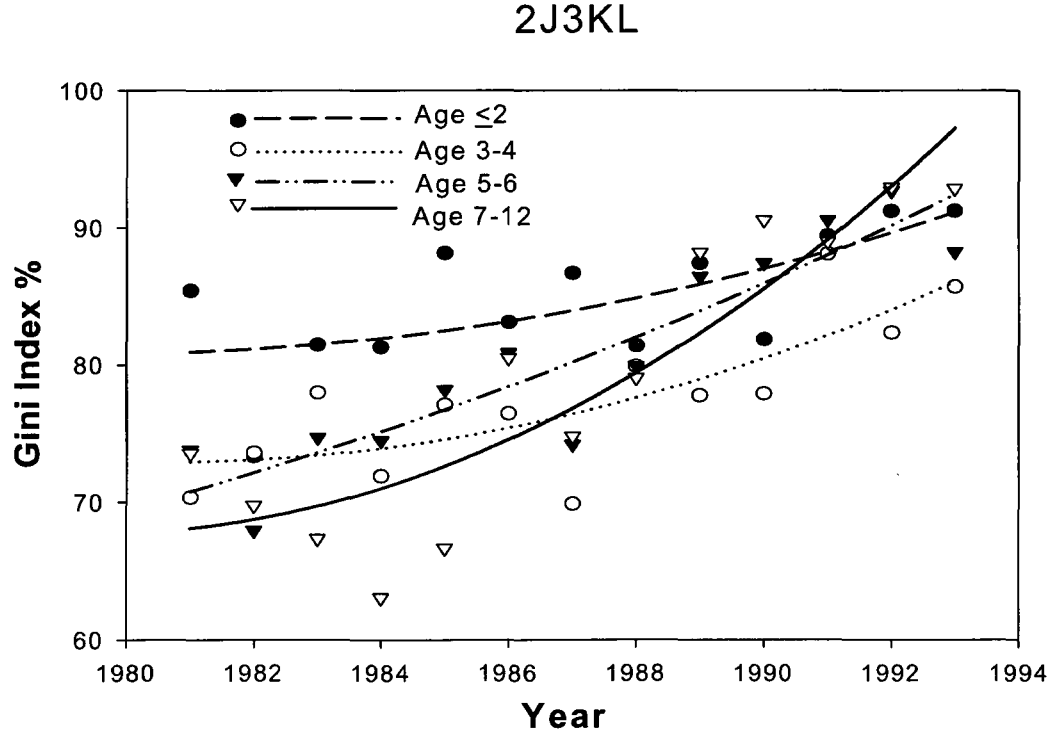

Figure 4.35. Gini index (%) for each age group from 1981 to 1993 in Divisions 2J3KL.

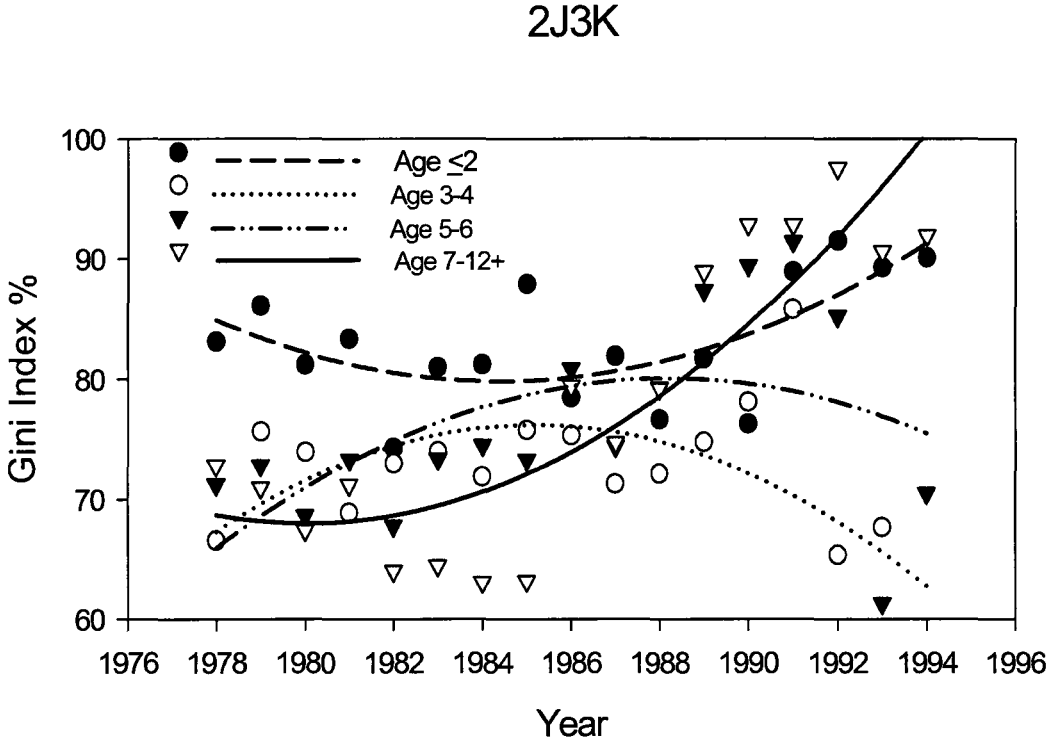

Figure 4.36. Gini index (%) for each age group from 1978 to 1994 in Divisions 2J3K.

4.2.2 Divisions 4RS

In divisions 4RS, Atlantic cod ages 7-12+, showed the greatest increase in the Gini index rising from 80% in the 1980s to 90% in the early 1990s (Figure 4.37). Ages 5-6 started at a higher Gini index in the early 1980s at 80% compared to 70% in divisions 2J3KL. Juveniles (ages ≤2) behaved the same in 4RS as they did in divisions 2J3KL (Figure 4.35) and divisions 2J3K (Figure 4.36) with a Gini index consistently high at around 80-90%. They did not show an increase in aggregation during the collapse (early 1990s). Atlantic cod ages 3-4 behaved differently in 4RS than in 2J3KL (1981-1994). The Gini index (degree of aggregation) declined in the early 1990s instead of increasing; the Gini index started at close to 70% in the early 1980s, and increased to 80% in the mid 1980s then decreased again to around 70% in the early 1990s. This pattern is similar to

that found in divisions 2J3K (78-94), where the Gini index for cod ages 3-4 ranged between 60-70% and decreased in the early 1990s.

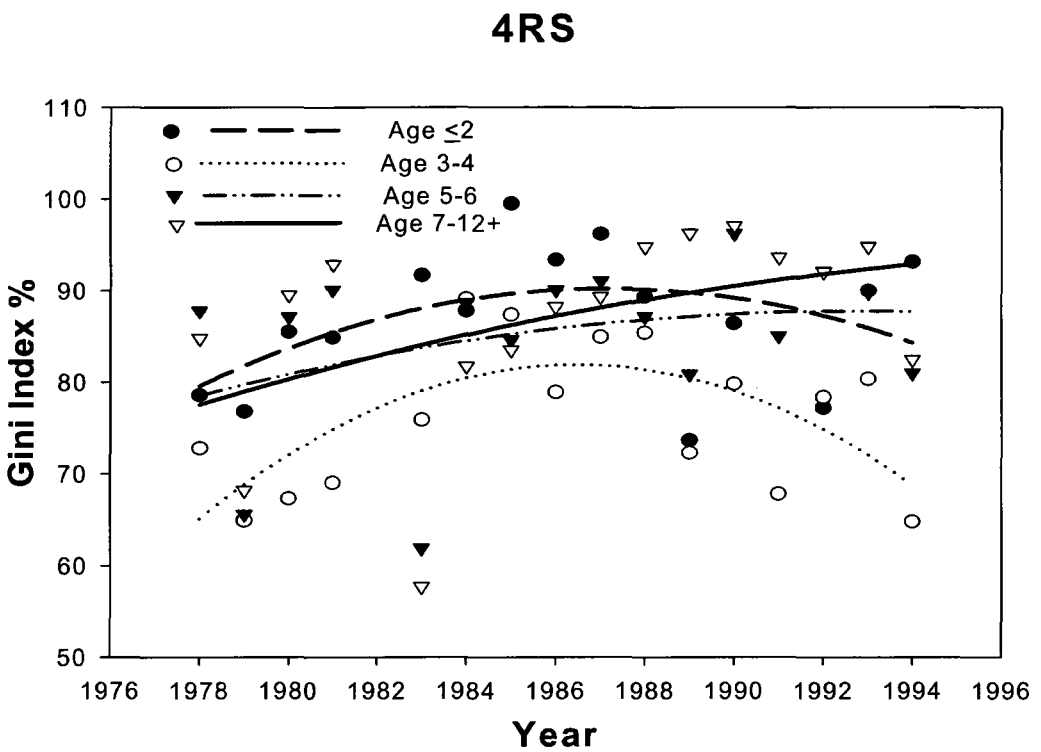

Figure 4.37. Gini index (%) for each age group from 1978 to 1994 in Divisions 4RS.

4.3 Variance

Variance in catch of Atlantic cod among tows by age class was calculated for 2J3KL from 1981-1994 (Figure 4.38) and for divisions 4RS from 1978-1994 (Figure 4.39) for age groups ≤2, 3-4, 5-6, and 7-12+ (Figure 4.38 and 4.39). The variance showed several peaks over time, which could be interpreted as peaks in aggregation. However, a comparison of these peaks with the mean values (Figures 4.38 and 4.39) shows that the variance is strongly driven by the mean. This was evident in 1986, which showed peak

abundance in 2J3KL for all age groups. In 1991, in divisions 4RS (Figure 4.39), the mean was associated with the variance with a peak of over 1.6 x 10^7 for ages 7-12+.

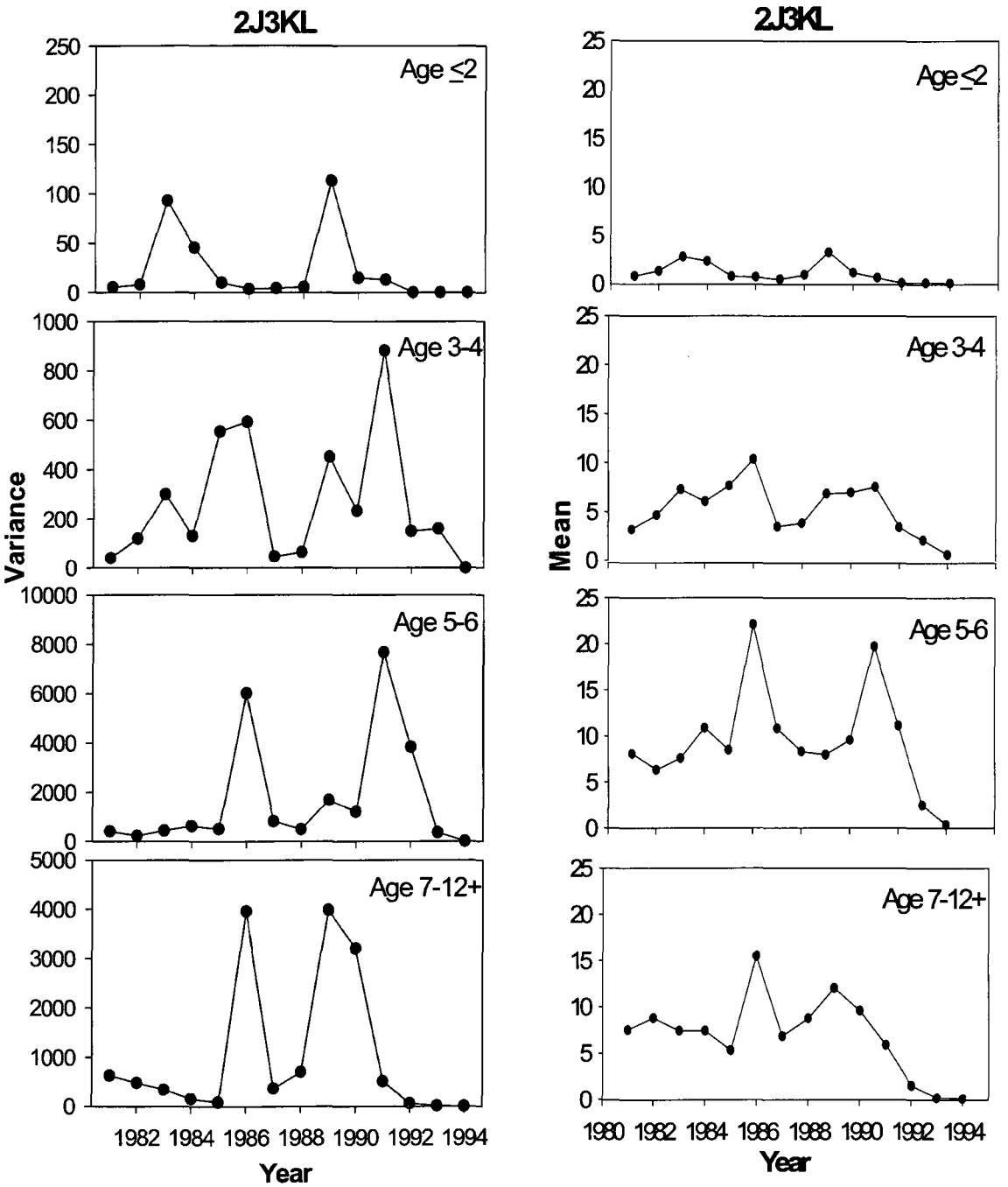

Figure 4.38. Variance and mean of standardized catch for each age group in Divisions 2J3KL from 1981-1994.

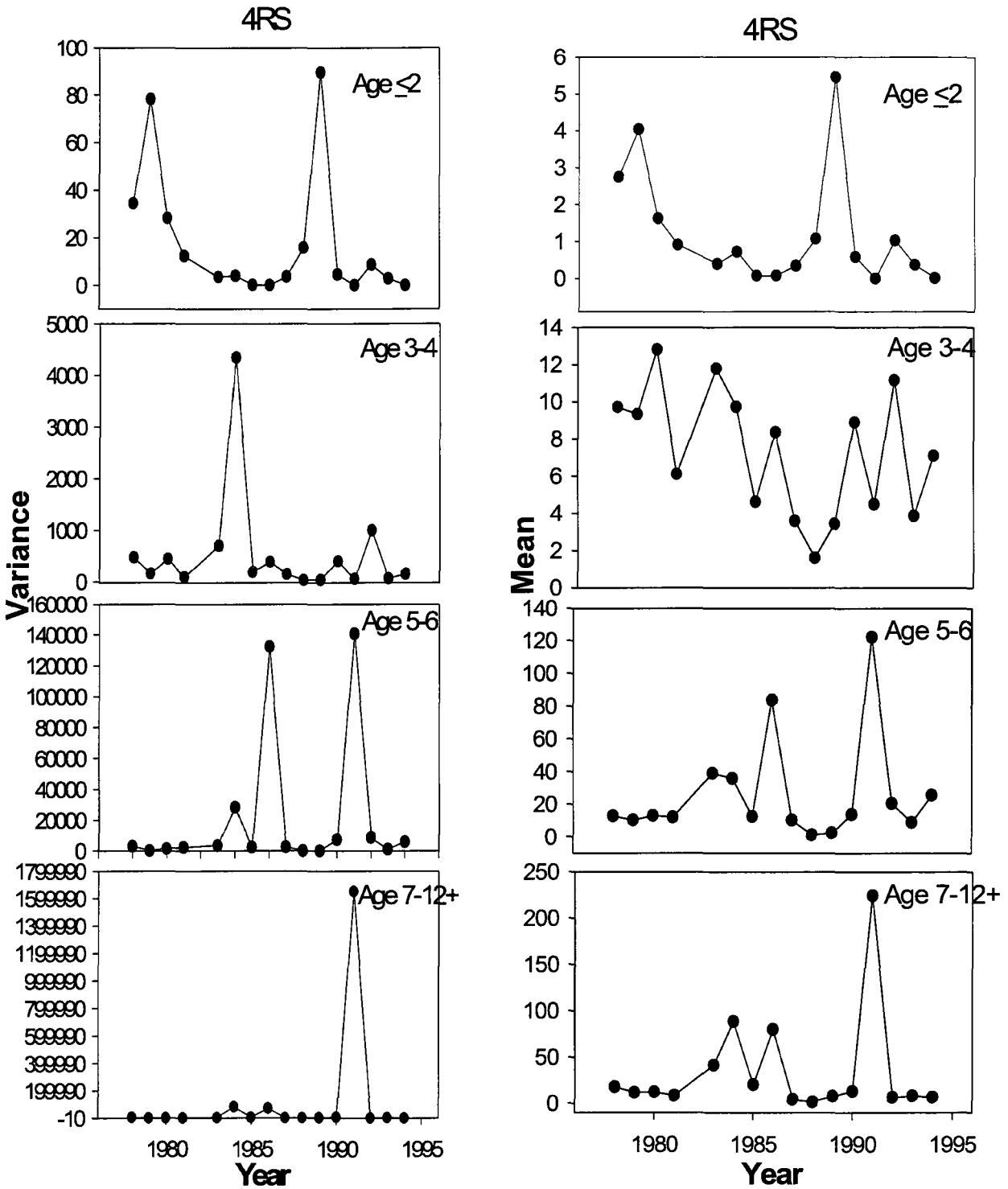

Figure 4.39. Variance and Mean standardized catch for each age group in Division 4RS from 1978 to 1994.

4.4 Power Law Exponent

As shown in Figures 4.38 and 4.39, variance depends on the mean, and therefore is of limited value in measuring aggregation. The power law exponent is a more sophisticated measure to account for the variance-mean relationship, by regressing the variance against the mean (Perry 1981). However in this case the power law exponent does not reveal a clear pattern of change in aggregation over time. The power law exponent was estimated for all ages (<2-12+) for all years (1978-1994) in divisions 2J, 3K, and 4RS and from 1981-1994 in division 3L. The exponent (slope of the power law regression) quantifies the change in the index of aggregation over time and ages. As the slope (exponent of power law) increases the degree of aggregation increases.

In divisions 2J, 3K and 3L the power law exponent increased in the early 1990s, pre-collapse and post collapse, and quickly decreased starting in 1994, when there were limited fish in the samples and thus a low mean and low variance (Figure 4.40). In division 2J, the slope range between 1.8 and 2.1, declining to 1.5 at age 10. Division 3K showed a different pattern as the slope increased, peaking at age 9, and differed even more in division 3L, where it peaked at ages 4, 5, and 6 then steadily declined (Figure 4.39). In 4RS the exponent of the power law showed a peak in aggregation at ages 5-6 followed by a gradual decline in the older ages (Figure 4.41). The slope ranged between 1.7 and 2.0 from 1978 to 1988, and then declined in 1989 before it peaked again in the early 1990s (Figure 4.41). This pattern is consistent with the pattern in the Gini index measure of aggregation in Divisions 2J3KL and 4RS (Figure 4.35).

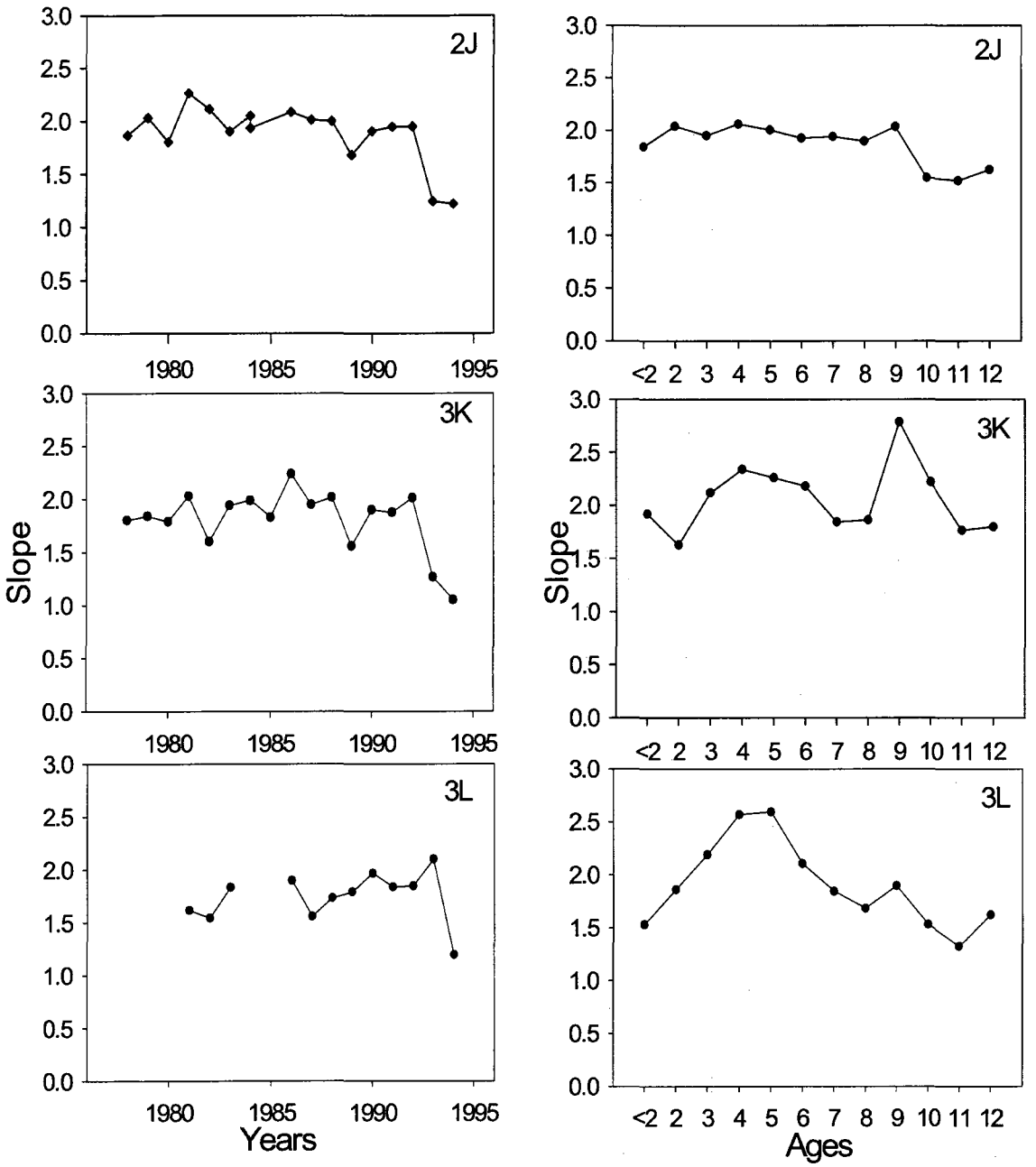

Figure 4.40. Power Law exponents for each division (2J, 3K, 3L) over time (1978-1994) and over ages <2-12+.

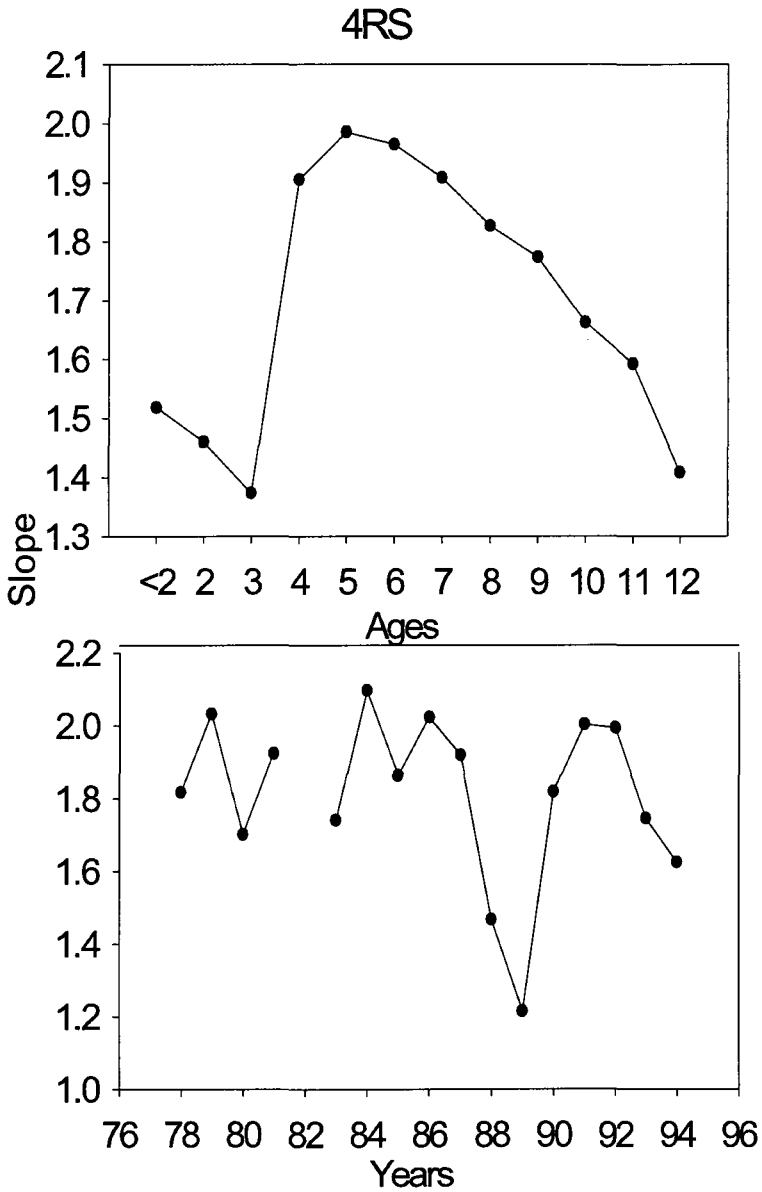

Figure 4.41. Power Law exponents for Division 4RS over ages <2-12+ and over time (1978-1994).

4.5 Frequency Distributions and Cumulative Frequency Distributions

The frequency distribution and cumulative frequency distribution were plotted for each age (<2-12+) over time (1978-1994) for divisions 2J3K and 4RS and for 2J3KL (1981-1994). These indices did not show any distinguishable difference between age groups, nor did they show any change in aggregation over time. Shown below is an example of age 6 in 4RS in 1986 and age 7 in divisions 2J3KL in 1986 (Figure 4.42) (see Appendix B for more examples). The frequency distributions display large number of tows with zero fish and the presence of a few high counts.

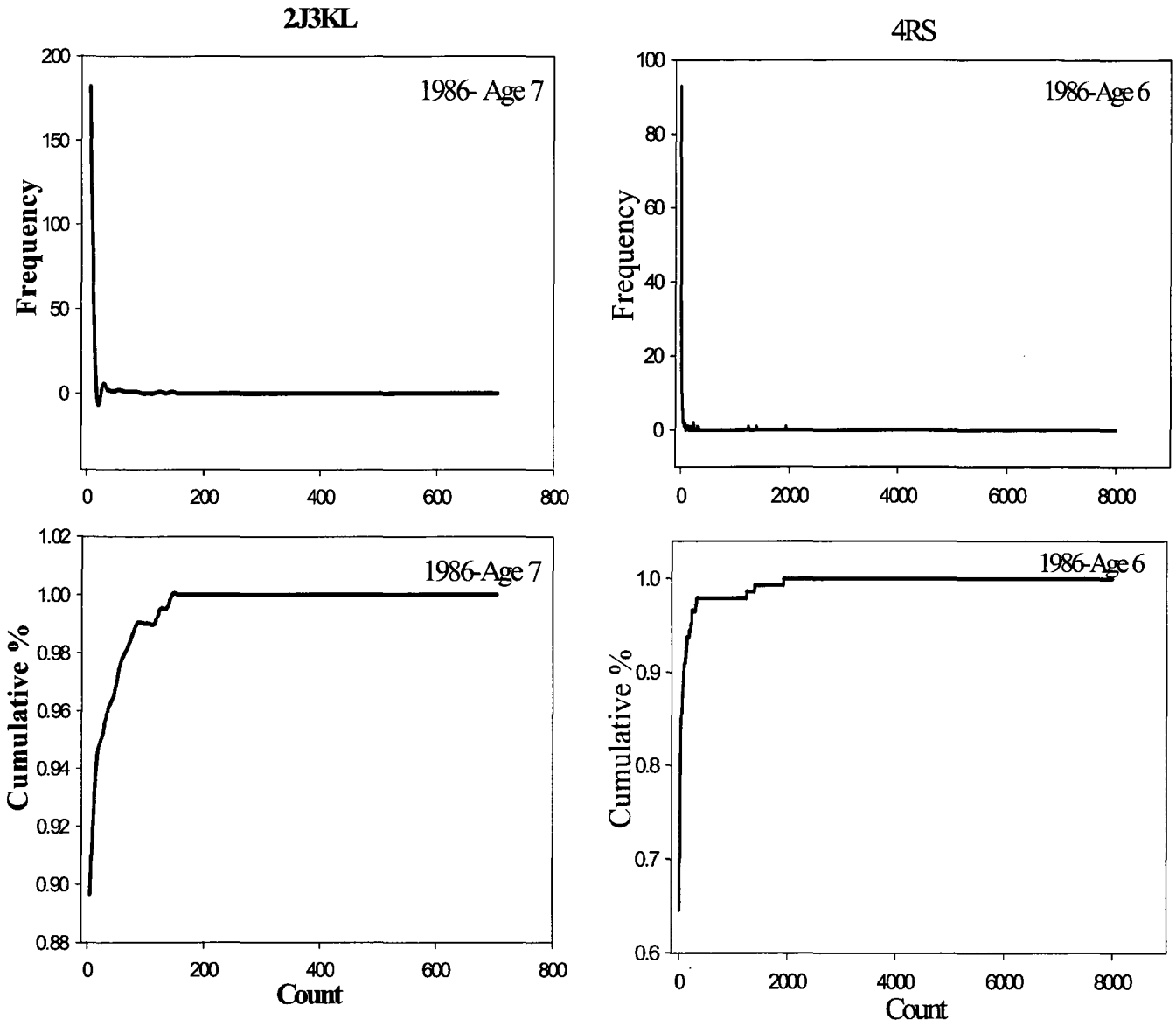

Figure 4.42. Cumulative frequency and Frequency distributions for Age 7 in Divisions 2J3KL and for Age 6 in Divisions 4RS in 1986.

4.6 Skewness

Skewness is used as a measure of the degree of asymmetry of a distribution around its mean. Skewness was calculated for all ages (<2-12+) over time (1978-1994) for each area 2J3KL and 4RS. This index showed differences between cod of different ages, however it did not show any change in aggregation over time. As shown in Figure 4.44, skewness over time (1978-1994) displayed the same pattern for ages 4, 5, and 6 in Divisions 2J3KL and 4RS, and also for ages 7, 8, and 9. There were no distinguishable differences based on age (Figure 4.43). However the younger fish showed a different pattern in divisions 4RS where ages <2 showed an increase in 1988 of 10, and decreased to a skewness of 4 in 1994, which differed from the pattern shown for ages 2 and 3 (Figure 4.45). This measure did not show any distinct change in aggregation over time and therefore is deemed a poor measure of aggregation relative to other measures used in this thesis.

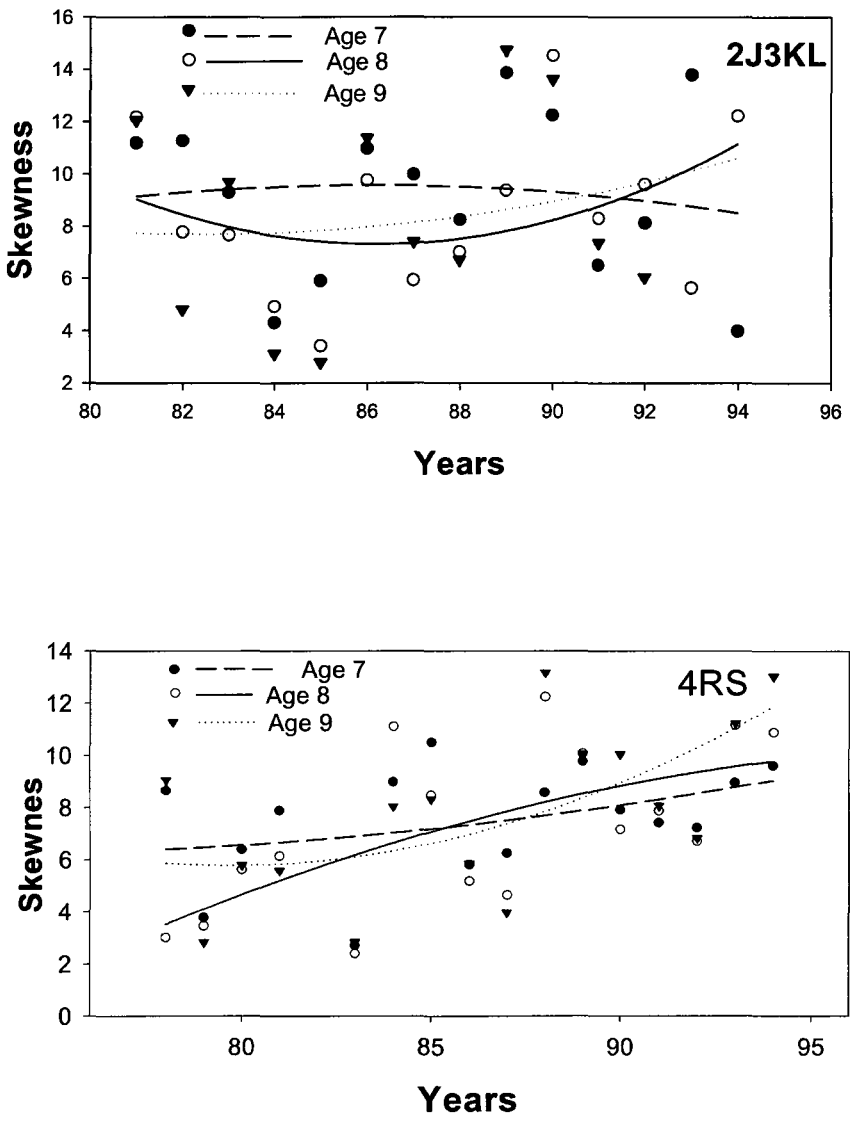

Figure 4.43. Skewness over time for ages 7, 8 and 9 in Divisions 2J3KL and 4RS.

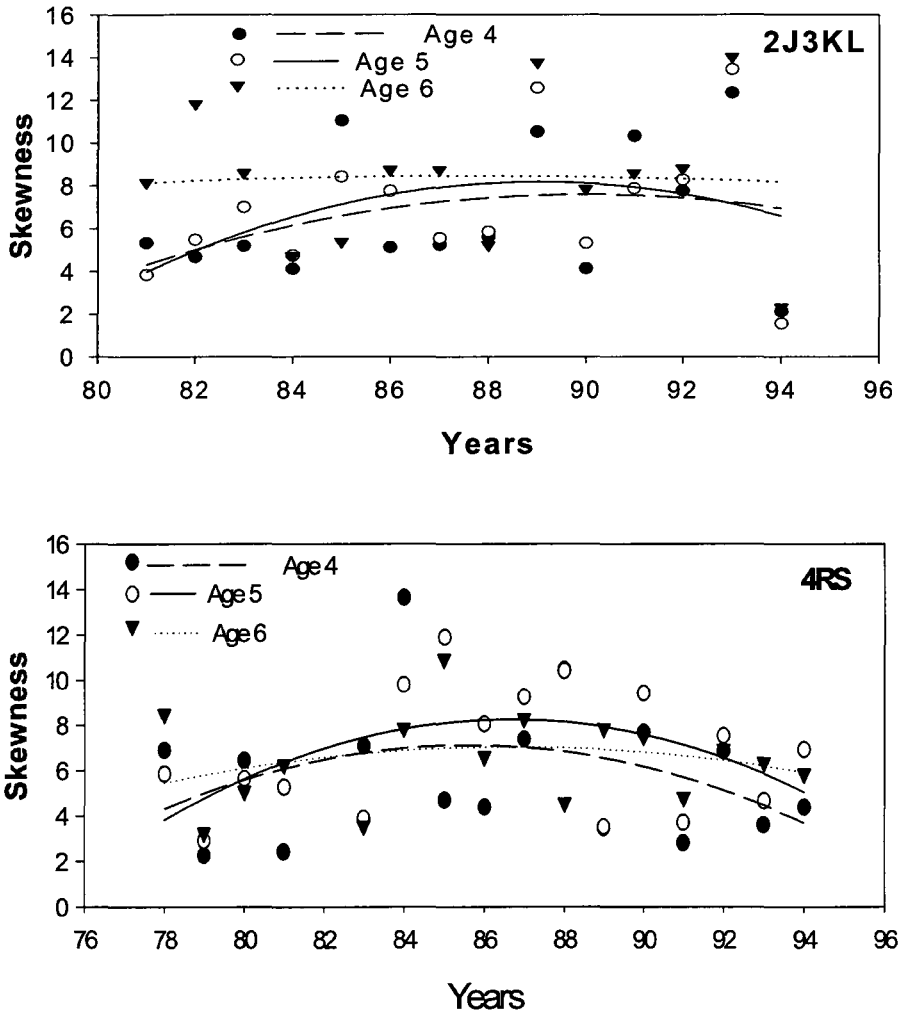

Figure 4.44. Skewness over time for ages 4, 5 and 6 in Divisions 2J3KL and 4RS.

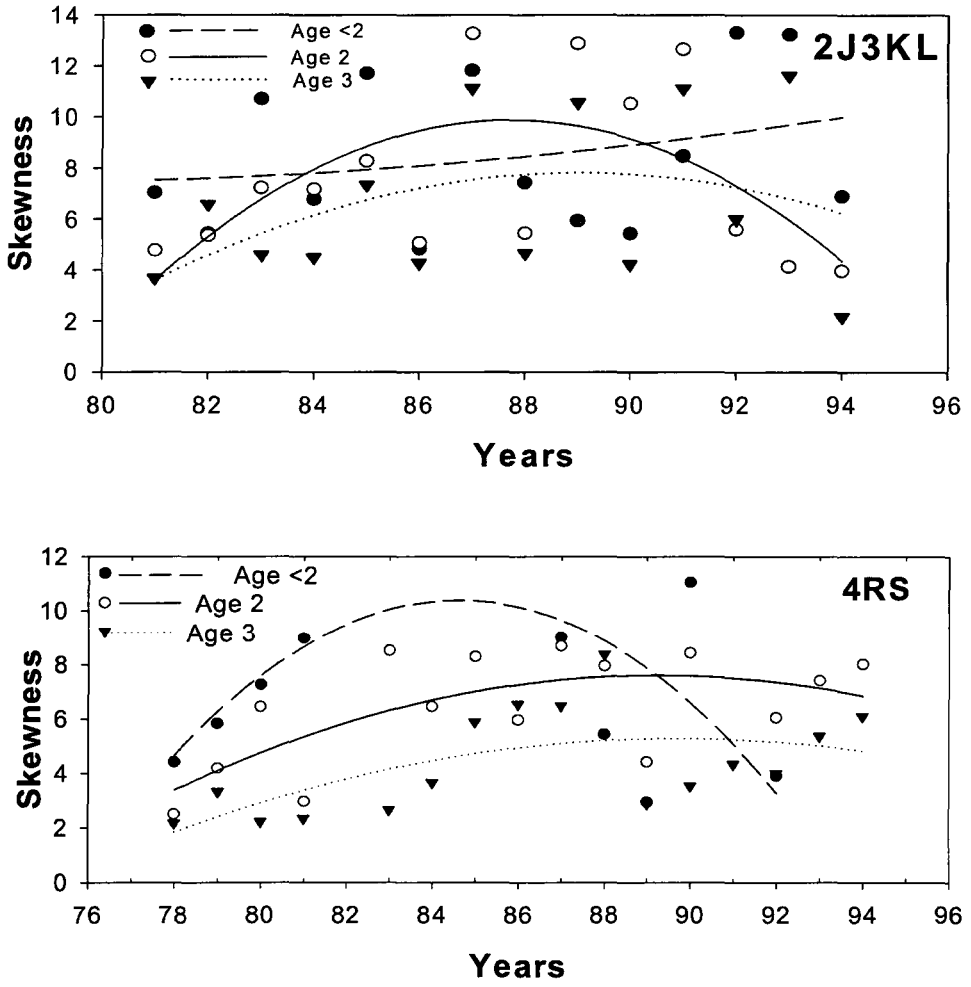

Figure 4.45. Skewness over time for ages <2, 2 and 3 in Divisions 2J3KL and 4RS.

Chapter 5: Discussion

Did the level of aggregation change over time in multiple age classes of Atlantic cod (*Gadus morhua*) in divisions 2J3KL and 4RS between 1978 -1994? The analysis of research vessel data from that period showed that, overall, older Atlantic cod became increasingly aggregated as stocks decreased in both areas. This is consistent with previous studies showing that for both areas Atlantic cod stock aggregation changed during the period of time leading up to stock collapse (Rose *et al.* 1994, Hutchings 1996, Smedbol *et al.* 2002, Myers and Cadigan 1995, Castonguay *et al.* 1999). The comparative analysis by age class that I did here showed that the highest degree of aggregation was in the older fish ages 7-12+ in both areas (2J3KL and 4RS). Age groups 3-4 and 5-6 did show a change in aggregation over time, but the degree of aggregation was not as prominent as with the older fish. The juveniles (ages ≤ 2) showed an even lesser change in aggregation over time. Surprisingly, juveniles started off highly aggregated according to the Gini index measure and stayed aggregated year after year. This could be attributed to the large numbers of tows with no juvenile fish in the R.V. data. A high frequency of low fish counts, with a few high fish counts, causes an increase in the Lorenz curve, and in turn increases the Gini index.

Several methods were used in this analysis of age-linked aggregation patterns over time including visual inspection of distribution maps, as well as multiple quantitative measures including the Gini index, variance and mean, power law exponent, frequency distribution and cumulative frequency distributions, and skewness. The clearest indication of change in aggregation between age groups, and over time was shown by the Gini

index, and by the visual inspection of the distribution maps. The highest degree of aggregation was demonstrated by the mature cod in both study areas (divisions 2J3KL and 4RS). In addition as the population shrinks, the number of geographical locations shrinks, but not necessarily at the same site each year.

5.1 Comparison of Distribution Maps to Quantitative measures

The distribution maps aided in visualizing how stock abundance and aggregation changed over time for each of the 4 age groups in 2J3KL and 4RS. The quantitative measures showed that aggregation trends varied between age groups of Atlantic cod, and that aggregation did indeed change over time. The geographic locations of the aggregations were not identified by any of the quantitative measures while they are evident from the maps.

While there were consistencies between the results from the distribution maps and the Gini index, there were important differences also. A visual interpretation of the maps of juvenile cod distribution in divisions 2J3KL showed that the distribution was spread out for several years. This pattern is not consistent with the high Gini index for these cod. The high Gini index in this case is driven by the large number of tows with 0 fish. The Gini index did not change much over time suggesting that the level of aggregation did not change over time (1978-1994).

In divisions 4RS, it was visually evident from the distribution maps that there was a low abundance of juveniles in the tows and no aggregation throughout all years. In contrast, the Gini index remained consistent over time for these juveniles at around 80%. While the variance and mean showed peaks in the early 1990s (Figure 4.39), which also

appear in the distribution maps, as there were trawls with few high counts in 1990 and 1991. In addition the power law exponent showed an increase in aggregation in the early 1990s followed by a decrease in 1994.

In divisions 2J3K (1978-1994), and 3L (1981-1994) (Figure 4.40) the power law exponent results for all ages were less consistent than the picture that emerges from the distribution maps. The only change in aggregation consistent with a peak in the power law exponent (Figure 4.40) occured in the early 1990s. The cumulative frequency distribution, and frequency distribution tables (Figure 4.42) were not consistent with what appears on the distribution maps. There was no change in aggregation displayed in these indices. The measure of skewness did not give a clear view of the change in aggregation. An analysis of changes in aggregation for different age groups using skewness (Figures 4.43, 4.44 and 4.45) did not show any distinct patterns of change in aggregation.

For ages 3-4 and 5-6 in divisions 2J3KL, aggregations started to appear after 1984 in the distribution maps, to different degrees, as the abundance fluctuated. This increase in aggregation was also evident in the Gini index graph where the increase in the Gini index (aggregation) started after 1984. However, the Gini index for 2J3K from 1978-1994 showed an increase in aggregation for cod ages 3-4 in the early 1990s. The variance and mean in ages 3-4 and ages 5-6 peaked in 1985-1986 and in 1992. This is consistent with the picture that emerges from the distribution maps as they show high degrees of aggregation, especially in 1992 when the stock collapsed. The power law exponent also showed an increase in aggregation in 1992, and a decrease in 1994.

Ages 3-4 in divisions 4RS showed a lower Gini index than in 2J3KL and the index did not increase as it did in 2J3KL. The Gini index was consistent with a visual

interpretation of the distribution maps in that both show ages 3-4 remained spread out and did not aggregate over time. It appears these cod only aggregated along the Esquiman Channel in the early 1990s. Ages 5-6 showed a greater degree of aggregation than age 3-4 cod in both the Gini index, and the distribution maps. The variance peaked in the early 1990s, which is consistent with the distribution maps where aggregation off of Port aux Basques was evident.

The older cod ages 7-12+ in divisions 2J3KL showed the highest degree of aggregation in the distribution maps, particularly in the early 1990s. This is consistent with the Gini index for these fish, as the Gini index showed a steep increase after 1984. The variance peaked in 1989 and 1990 for the older cod, and peaked in 1992. The distribution maps for 1988-1990 show aggregations for ages 7-12+ on the 3KL border, and in the northern part of 3K, as well as on the nose of the Grand Bank. This is consistent with the steep increase in aggregation as measured by the Gini index for ages 7-12+ in 1992. The degree of aggregation was prominent for ages 7-12+ on the distribution maps and this is also consistent with the peaks in variance in Figure 4.37. The power law exponent did not display this increase in aggregation in the older fish. In 2J3KL (Figure 4.40) the power law exponent remained high until ages 9 and 10, then decreased quickly, which is not consistent with other measures, notably the Gini index.

In 4RS the older fish, ages 7-12+ showed the highest degree of aggregation near the Cabot Strait (off of Port aux Basques) in the distribution maps in the early 1990s. This is consistent with the steep increase in the Gini index (Figure 4.37), and also in the measures of variance and mean (Figure 4.39), as well as the power law exponent.

Overall the distribution maps and the Gini index displayed the same picture of changes in aggregation over time. The change in aggregation showed the steepest increase in the early 1990s, for the older fish in both areas.

5.2 Comparison of Divisions 4RS and 2J3KL

The stratified random surveys took place during the autumn in divisions 2J3KL, and in the winter season in divisions 4RS (Northern Gulf of St. Lawrence). Seasonal change in fish behavior would be expected to cause some difference in patterns of aggregation in the two areas. During the winter months in the Northern Gulf of St. Lawrence, the cod form over-wintering aggregations and also start to form pre-spawning aggregations (in March and April) as they are preparing to spawn in the spring (Ouellet *et al.* 1997). The increase in the degree of aggregation in divisions 4RS could be attributed to either one or both of these aggregative behaviors.

In division 2J3KL cod do not spawn until early spring, and normally do not form over -wintering aggregations until December-January. However, there is evidence that cod in 2J3KL began moving into over-wintering aggregations earlier in the autumn season (during the research trawl survey) in the 1990s (George Lilly, Fisheries and Oceans Canada, St. John's, NL, personal communication). The northern Gulf cod were also found to form over-wintering aggregations in the autumn season in the 1990s due to changes in temperatures in 4RS (Castonguay *et al.* 1999).

Geographically there are important and large differences between these two areas. The Northern Gulf of St. Lawrence (divisions 4RS) has several river systems running into it, along with channels to the North Atlantic. The area overall is shallower and reaches its deepest range near the Cabot Strait at over 400 m. Divisions 2J3KL (southern Labrador

and eastern Newfoundland) extend from the Hamilton Bank to the Grand Banks, and out to the continental slope; the latter can reach depths in excess of 1000 m. Cod can change their distribution and aggregative behavior in response to depth, temperature, and latitudinal shifts (Castonguay *et al.* 1999). Despite these differences there are similarities in the behavior of cod in divisions 2J3KL and 4RS. In both areas older cod (ages 7-12+) aggregated in the early 1990s during low stock abundance (Figure 4.15 and Figure 4.33).

In 1985 aggregations started to form in geographically fixed locations in both areas: near the Bonavista corridor in divisions 2J3KL and near the Port au Port Peninsula and the Cabot Strait in divisions 4RS (Figure 3.1). The aggregations near the Bonavista corridor dwindled to one aggregation near the nose of the Grand Banks in 1992 and that eventually disappeared in 1994. In divisions 4RS cod ages 5-6 and 7-12+ became aggregated in 1985 (Figure 4.24) and became heavily aggregated in the early 1990s (Figure 4.30) near the Cabot Strait until 1994. These cod aggregations in fixed locations during a period of low abundance could provide support for the basin model which predicts that density-dependent populations will tend to contract toward the most favorable habitat as they are fished down (MacCall 1990, Hilborn and Walters 1992). In this case, the older cod seemed to collapse into fixed locations as their density declined. In 2J3KL the last aggregation shown in Figure 4.15 decreased to minimal numbers of cod in 1994.

During the surveys in both areas, the cod aggregations could have been forming to over-winter, despite the difference in timing. In 2J3KL the research surveys were conducted in the autumn months (October- December). Cod in divisions 2J3KL normally form over-wintering aggregations starting in January. Early over-wintering aggregations

could have been caught in the survey. In divisions 4RS, the winter survey starts in January. These surveys could have caught over-wintering cod aggregations that started to form during that period of time. The Gini index displayed the steepest increase in aggregation for ages 7-12+ in both areas. In the early 1990s this age group showed a prominent increase in aggregation just prior to the collapse with these aggregations being located near Port aux Basques off southwestern Newfoundland and near the Bonavista corridor area in divisions 2J3KL.

The Gini index for juvenile cod (≤ 2) showed no change over time in both areas (Figures 4.35 and 4.37). Aggregations among cod ages 3-4 showed different trends in the Gini index in the two areas. The Gini index increased in divisions 2J3KL from 1981-1994. At the same time in 4RS, the Gini index showed a slight decrease. However, the Gini index for cod ages 3-4 in divisions 2J3K (1978-1994) was similar to the Gini Index in 4RS and also showed a decrease. Cod ages 5-6 also showed different trends in the Gini index between the two areas (4RS and 2J3KL): in 2J3KL, the Gini index increased from 80% in the mid 1980s to 90% in the early 1990s whereas in 4RS there was a similar trend but the Gini index did not increase as much.

Measures of variance, mean, and the power law exponent all showed an increase in aggregation in the early 1990s, while the frequency distributions, cumulative frequency distributions, and skewness measures did not show distinct change in aggregation over time. The variance and mean showed peaks in 1986 and in the early 1990s in both areas. In both 2J3KL and 4RS, the power law exponent showed an increase in the early 1990s followed by a decrease in 1994.

5.3 Comparison between Quantitative Measures

Based on my results the most informative quantitative measure of aggregation was the Gini index. The Gini index showed the most prominent change in aggregation across age classes and in both divisions (2J3KL and 4RS) over time. Variance also showed change in aggregation over time as it reached a peak in the early 1990s in all divisions (2J3KL, 4RS) when aggregation was prominent. However, for aggregated count data the variance is driven by the mean, which makes it less reliable. Variance is less informative if it changes largely in concert with the mean. For example in Figure 4.39 cod ages 5-6 and 7-12+ showed the greatest peaks of aggregation in the measures of variance, and also showed the steepest increase in aggregation in divisions 2J3KL (1981-94) and 4RS (1978-94). However, the corresponding peaks in mean also drove these peaks in aggregation. The power law exponent, which is a more sophisticated measure of aggregation than the variance and mean (Perry 1981), surprisingly did not show a distinct change in aggregation. The power law did, however, show increase in the early 1990s when aggregation did occur in both areas. The other quantitative measures that were used including cumulative frequency distributions, frequency distributions, and skewness did not show any change in aggregation over time.

When comparing the measures of aggregation used in this thesis, the best measure that could potentially be used in stock assessments and for management would be the Gini index. This measure has recently been used by Smedbol (2002) in management reports, as well as in other papers (Myers and Cadigan 1995).

5.4 Limitations of the Analysis

5.4.1 Consequences of Using 4RS excluding 3Pn

Frechet and Gagnon (1993) found that in 1991 over 90% of cod in the winter survey had shifted deeper (>360m) along the Cabot Strait within divisions 3Pn and 4RS. This shift raises the question of whether the absence of 3Pn RV data affects the analysis of aggregation. Division 3Pn was not included in the analysis because it was outside the northern Gulf of St. Lawrence. My results show that there was a high degree of aggregation near the Port aux Basques area in the early 1990s. This aggregation appears to have been a result of cod forming over-wintering or pre-spawning aggregations in order to spawn in the early spring (Yvelin *et al.* 2005). According to Castonguay *et al.* (1999), who examined Atlantic cod distribution in divisions 3Pn & 4RS, this stock did indeed aggregate within southern 4R, and in division 3Pn near Port aux Basques. If we look at Figure 2 in Castonguay *et al.* (1999), which shows the distribution of cod on both sides of the boundary between 4R and 3Pn, there is no strong evidence of change in aggregative behavior in either division 4R or 3Pn. Thus, given what we know of the behavior of cod near the 3Pn boundary, and given the evidence from Castonguay *et al.* (1999) there is no reason to expect that the results concerning aggregative behavior of cod in this thesis were affected by the absence of 3Pn data from the analysis.

5.5 Contribution to the literature on changes in cod aggregation

My results were generally consistent with those from previous studies of change in aggregation during stock collapse (Myers and Cadigan 1995, Schneider *et al.* 1997,

Smedbol *et al.* 2002). My results show that the Gini index reached its peak in the early 1990s for Atlantic cod in both the northern Grand Banks (divisions 2J3KL) and northern Gulf of St. Lawrence (divisions 4RS) In both areas (Figure 4.35), the increase started after 1984. This increase is consistent with Myers and Cadigan (1995) who found that when the spawning stock biomass in divisions 2J3KL decreased in 1992, the Gini index for all age classes together reached its peak and increased after 1984. In my results the younger fish ages ≤ 2 did not show any change in aggregation over time, which can be attributed to the low count of juveniles caught in the tows. My findings are consistent with Schneider *et al.* (1997) who found that there was no contraction in range of juveniles sampled in inshore waters over time (from 1959-1964 and 1992-1994). My results demonstrate that the degree of aggregation was highest in the early 1990s when the stocks collapsed in 2J3KL (1992) and in 4RS (1994). Similar findings were also shown by Smedbol *et al.* (2002) who found that with a large decrease in abundance the degree of aggregation increased in multiple cod stocks. In 1987 and 1990 the distribution maps showed an increase in the degree of aggregation along the continental shelf (Figure 4.10 and Figure 4.13).

Hutchings (1996) found that the location of dense aggregations of northern cod was commonly near the edge of the continental shelf. Aggregations of cod were also consistently found in southern portions of division 3L on the Grand Bank. These aggregations were evident from 1984 to 1987 and in 1990 (Hutchings 1996). Taggart *et al.* (1994) also reported that mature cod ages 5+ aggregated in pockets along the shelf break. In 1992 the distribution maps showed a high degree of aggregation (Figure 4.15) for ages 5-6 and 7-12+. This is consistent with the high degree of aggregation Rose and

Kulka (1999) found near divisions 3KL (the Bonavista corridor) in the early 1990s, with more than 450 000 t of cod within an area of 7000 km^2. In my results the last aggregation along the shelf is shown in 1993 near the Bonavista corridor, which then disappears in 1994 (Figure 4.16 and Figure 4.17). According to Rose and Kulka (1999) the Bonavista corridor is the last area where large cod aggregations were observed.

Based on a visual inspection of the distribution maps (Figures 4.35 and 4.37) and the Gini index, high densities or increases in aggregation were found during periods of low abundance in the early 1990s in divisions 2J3KL and 4RS. Similar findings were shown by Swain and Wade (1993) who found that among cod ages 3-8 the highest cod densities occurred during low abundance periods in the western regions of the southern Gulf of St. Lawrence.

In my results the older fish were found in deeper waters than the juveniles and displayed a higher degree of aggregation in both areas, near the Cabot Strait (>360m) in the northern Gulf of St. Lawrence, and near the continental slope which extends down to 1000 m in divisions 2J3KL. This is consistent with Swain (1993) who found high densities of older fish (age 6-8+) in deeper waters.

5.6 Reasons for Changes in aggregation

5.6.1 Basin Model

The expansion and contraction of geographic range in relation to fluctuations in population abundance has been observed in many marine species, including pelagic (MacCall 1990, Winters and Wheeler 1985) and demersal fish (Swain and Wade 1993). Increasing and decreasing abundance are correlated with changes in geographic range that

are due to density dependence, according to MacCall's basin model (MacCall 1990). As fish abundance decreases the geographic range contracts, and density increases. The basin model is based on a premise of density dependent habitat selection, as density increases, at low population sizes, habitat selectivity decreases. Habitat could include change in temperatures, salinity levels, prey distribution and abundance of competitors.

The results of my study are consistent with the basin model in that the distribution maps show that older fish (Ages 7-12+) in divisions 2J3KL and 4RS collapsed into geographically fixed areas during periods of low abundance in the early 1990s in both areas. Visually the basin model seems to apply to the collapse of cod distribution in both 2J3KL and 4RS. As overall cod abundance decreased, aggregation increased and the range of distribution collapsed into fixed locations. As shown in Figures 4.12-4.15 from 1989 to 1992 this autumn survey showed the formation of aggregations along the shelf, which dwindled to one large aggregation in 1992 along the Bonavista Corridor. However, if this model did apply to Atlantic cod during periods of low abundance, then cod should also have aggregated to some degree during 1978-1979 when cod also reached low levels of abundance as shown in Figures 4.1 and 4.2. The basin model is thus not consistent with the longer term record of change in abundance. The juveniles showed no change in aggregation but show a consistently high degree of aggregation, which can be attributed to the consistently low counts of juveniles.

The basin model does not apply to the change in cod aggregation in either divisional area (2J3KL or 4RS). The alternative explanation for this increase in aggregation during periods of low abundance (cod collapse) is a simple consequence of annual spawning behavior. Density dependent habitat selection does not need to be

invoked here, aggregation as part of annual migration/spawning cycles allows aggregation at either fixed or several different geographical locations.

Several studies have examined whether temperature change can aggregate cod by driving them deeper. There is evidence that temperature compresses the distribution vertically or shifts it southward (Castonguay *et al.* 1999). However, vertical and lateral compression does not offer a simple explanation of aggregation at a small number of points along an isotherm that has been shifted southward or deeper. Aggregation as part of the migration/spawning cycle offers a simple explanation for aggregation at a small number of foci. This could act in conjunction with vertical compression or southward shifts.

5.7 Management Implications

Increased aggregation could potentially give a biased picture for commercial catch because CPUE remains high as long as the industry can find the aggregations. Cod started to aggregate in the late 1980s and early 1990s prior to the cod collapse, which allowed catches to remain high within limited areas, even though the stock was collapsing citation. In the late 1980s and early 1990s locally high densities gave a misleadingly high estimate of cod abundance (Rose and Kulka 1999). These high-density aggregations are shown in the results for older fish (ages 7-12+) in my results (Figure 4.15 and Figures 4.31-4.32). Fishermen continued to concentrate their efforts in areas of high cod abundance, responding to shifts in cod distribution and once they located these aggregations their effort concentrated in these areas (Rose and Leggett 1991). In turn the increase in cod aggregations increased the susceptibility of cod to the fishing gear, and as

a result contributed to the stock collapse (Hutchings 1996). For example, the aggregation in the Bonavista corridor in the early 1990s increased the vulnerability of the remaining fish to Canadian trawlers, and catch increased markedly in this area. The fishing effort concentrated in this area, and in turn aggregations were fished down. CPUE from the mobile gear fishery is an unstable measure for biomass estimates. Hilborn and Walters (1992) describe stocks where CPUE remains high as stocks decline, as exhibiting hyperstability. Castonguay *et al.* (1999) suggested that northern Gulf cod may have exhibited hyperstability in the early 1990s that led to increased CPUE as abundance was declining. Several studies have described the unreliability of CPUE as a linear relation to abundance for mobile fisheries for groundfish (Crecco and Overholtz 1990, Swain and Wade 1993, Rose and Leggett 1989). Rose and Kulka (1998) explored the theory that CPUE was unlikely to track changes in stock abundance. They found that CPUE increased during the cod collapse, which verifies that CPUE is an unstable measure for stock abundance.

The results of this study showed that the increase in aggregation did not occur uniformly in all age groups. Rather, the change in aggregation occurred more strongly in recently matured age classes than in pre-reproductive age classes. Atlantic cod in this age group are known as the spawner biomass, and are the driving forces of any fish stock. Once these older cod are fished down, the stock will diminish as a whole and it will take a longer time for recovery to occur. As shown in this study the age classes aggregated to different degrees. Quantitative measures (Gini index) showed patterns of change in aggregation, and distribution maps were used to visually interpret these changes over time.

It is essential to use sound abundance indices for fisheries management. The collapse of the cod fishery in the northwest Atlantic is a commonly cited example of how overestimation of fish abundance can contribute to a collapse. Management measures should be conservative enough to prevent overexploitation of a fish stock. This study shows that aggregation increases with decreasing stock size in a demersal species, depending on age, a result with important implications for management. Spatial structure and degree of aggregation should be monitored and displayed for all demersal species, not just for management of pelagic species. In this instance, when evaluating cod aggregation during a collapse a measure of aggregation that performs well, the Gini index, should be considered in science advice to management.

6.0 References

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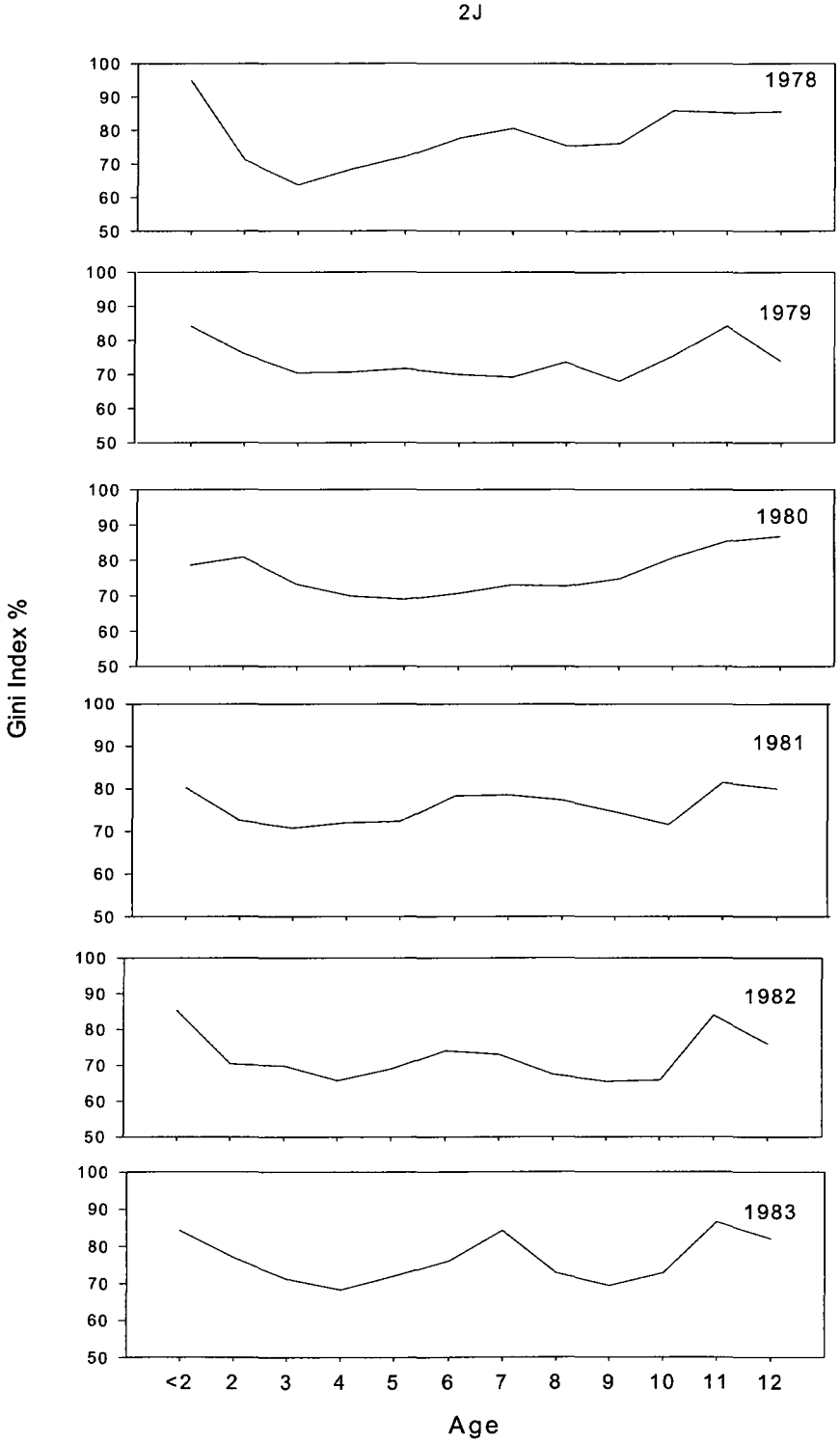
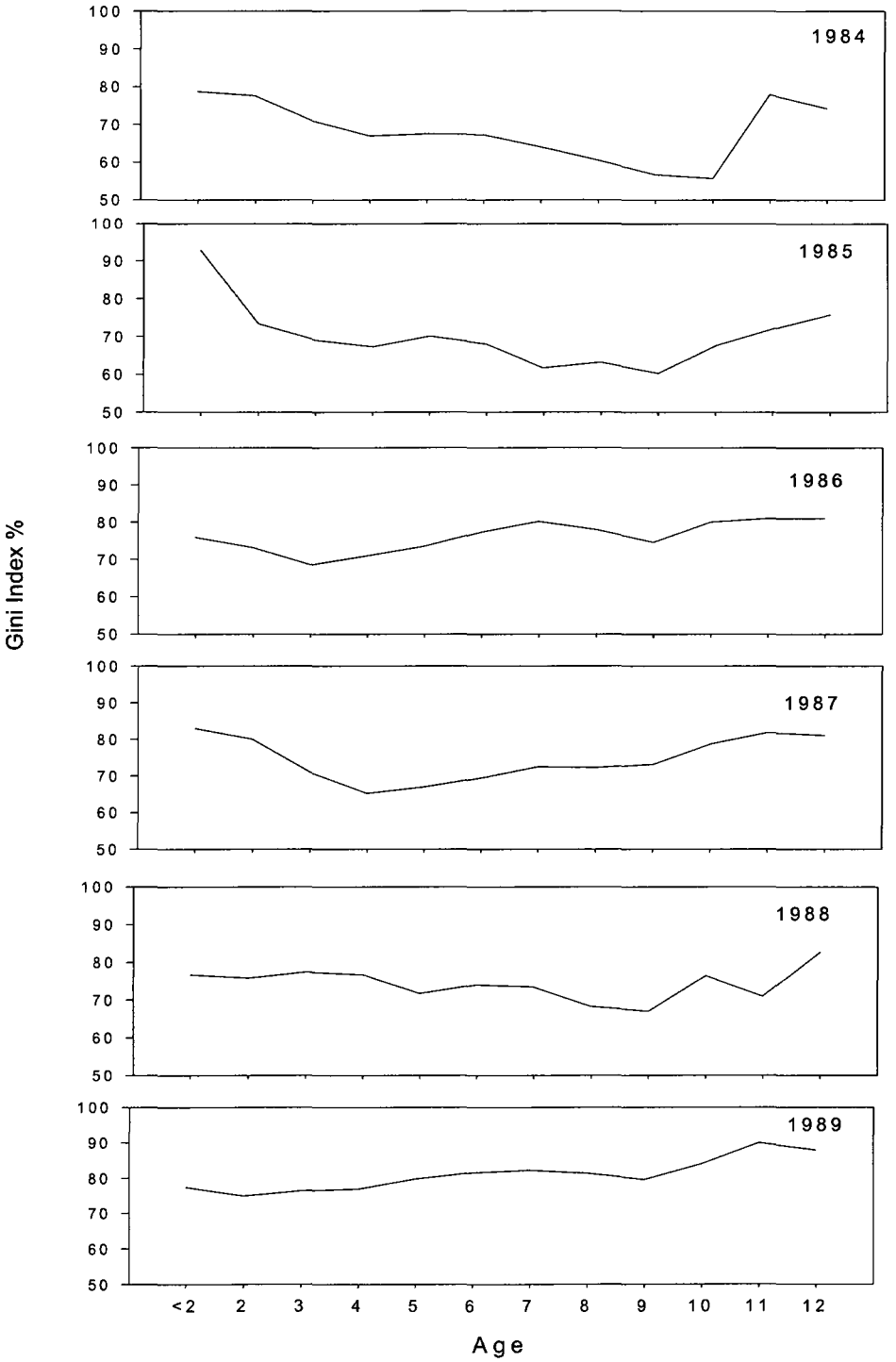
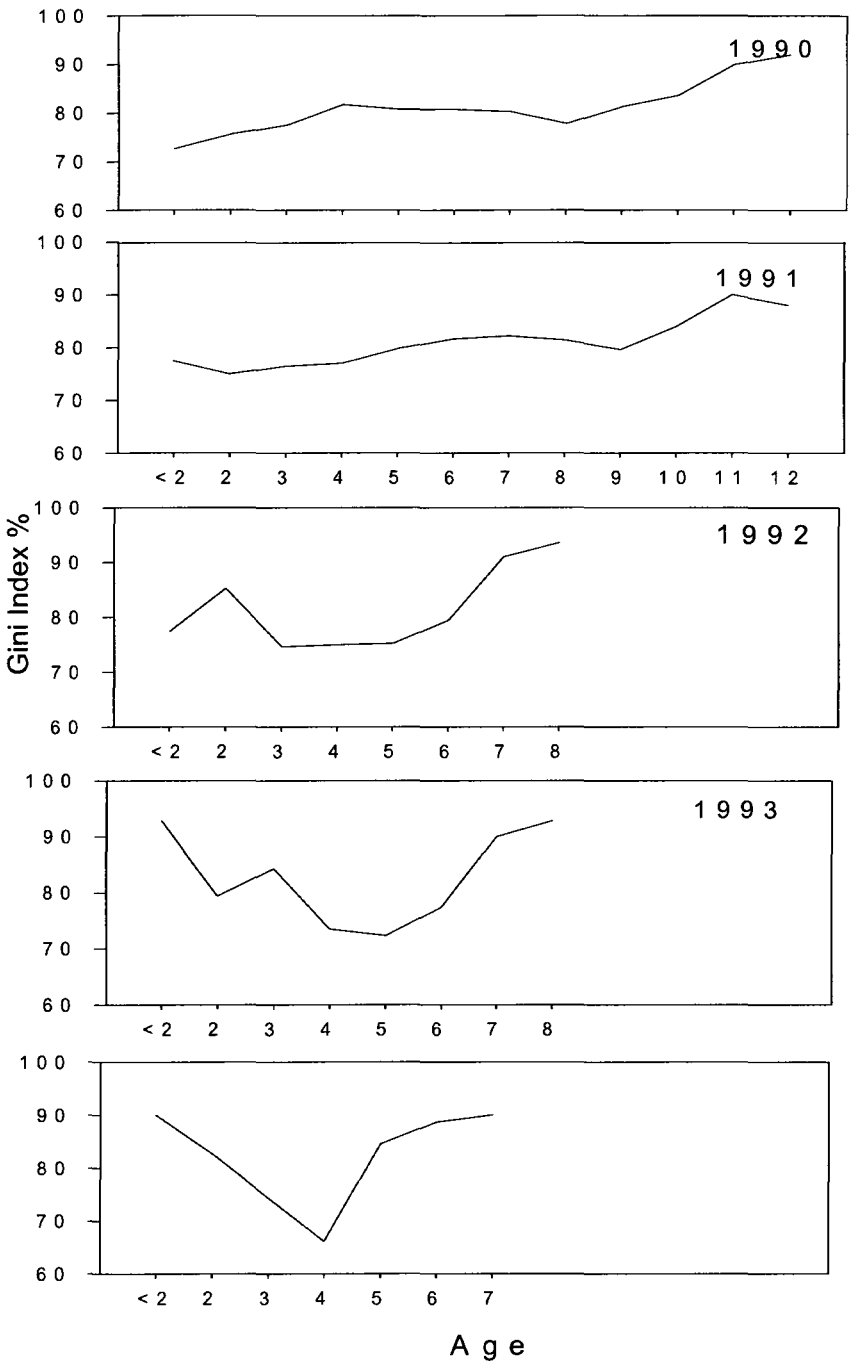
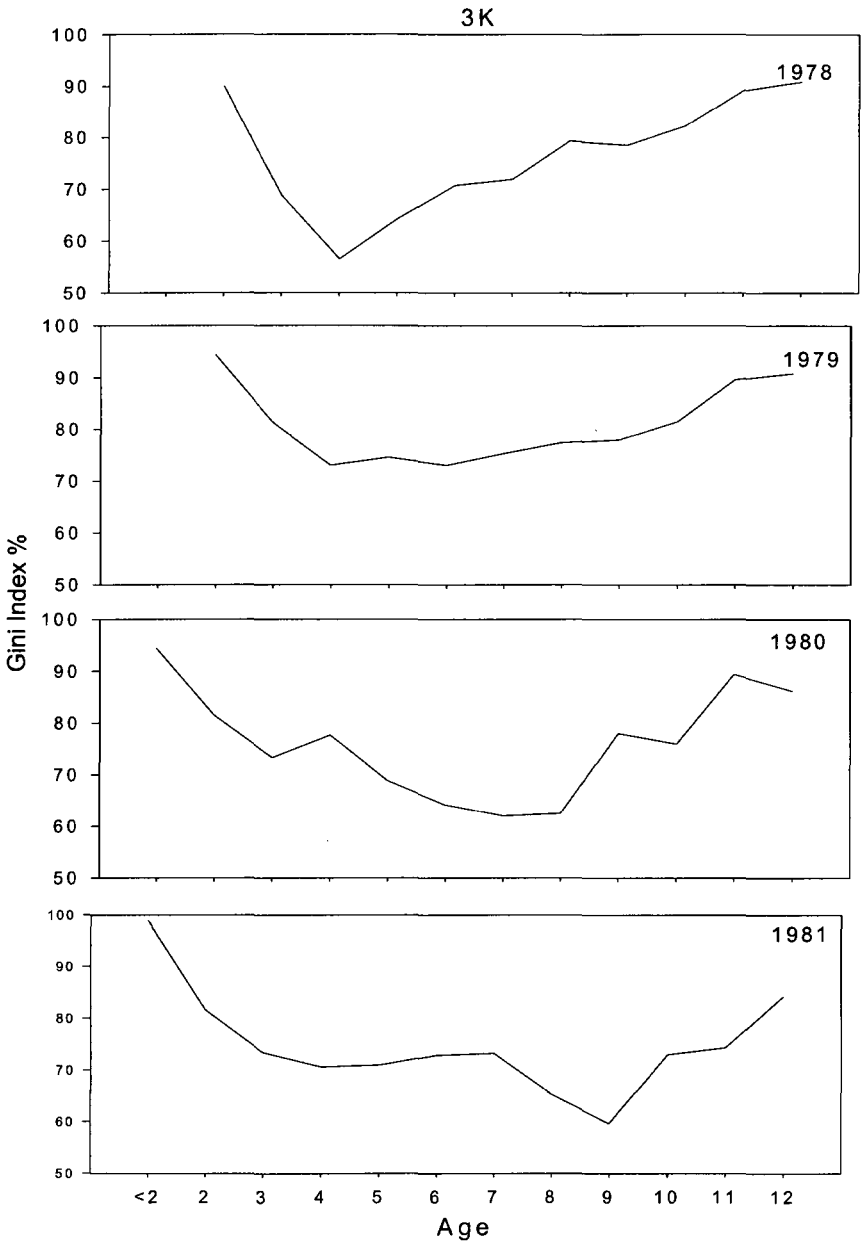
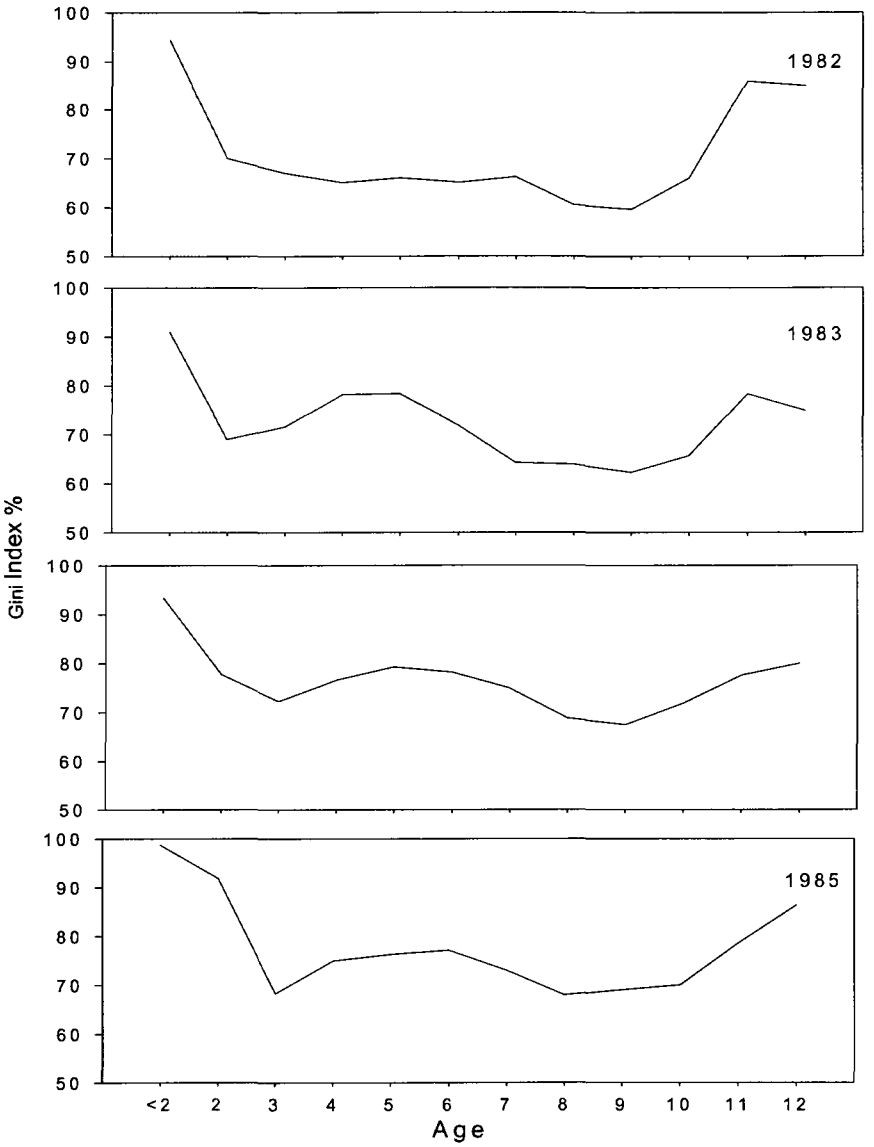
Appendix A: Gini index for each age for divisions 2J, 3K and 3L from 1978 to 1994.

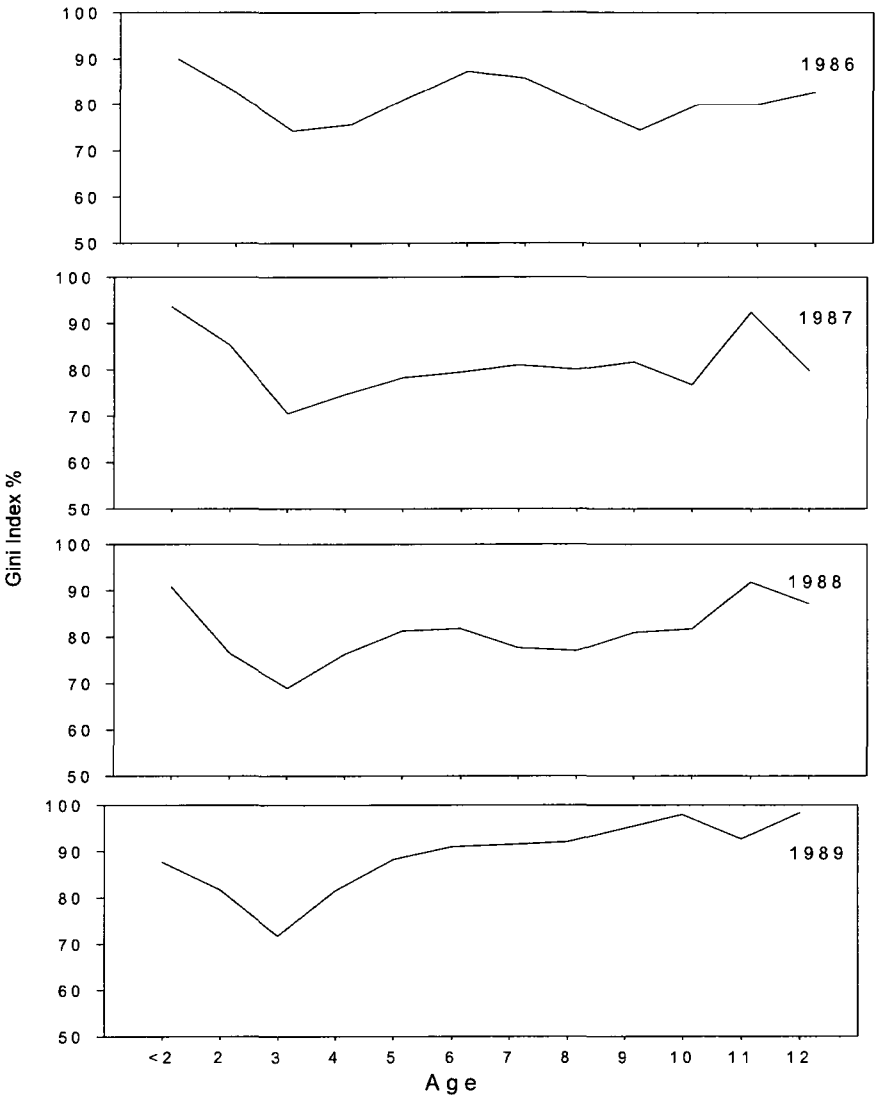


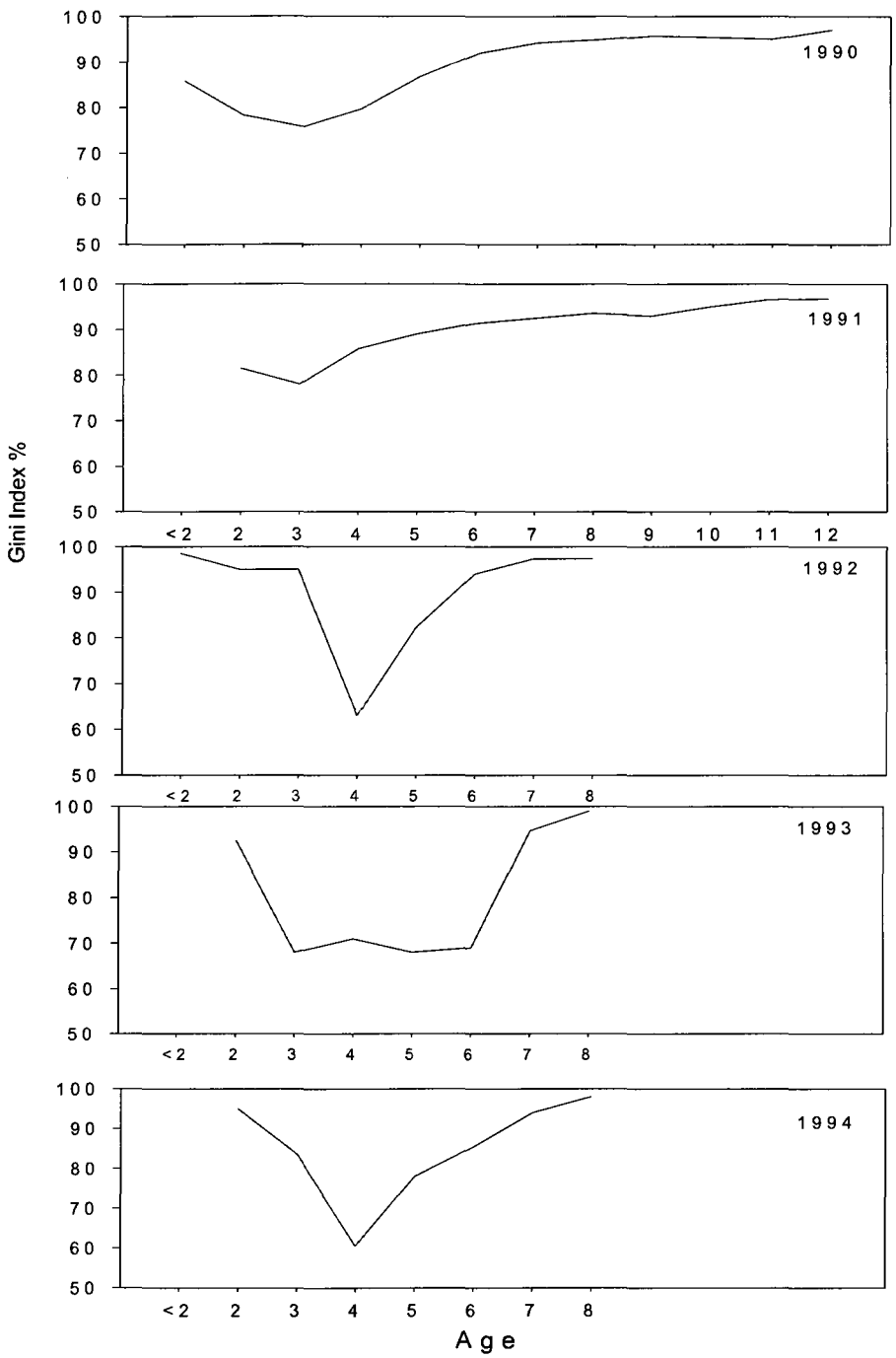

Gini Index %
100
90
80
70
60
50
1984
1985
1986
1987
1988
1989
<2
2
3
4
5
6
7
8
9
10
11
12
Age

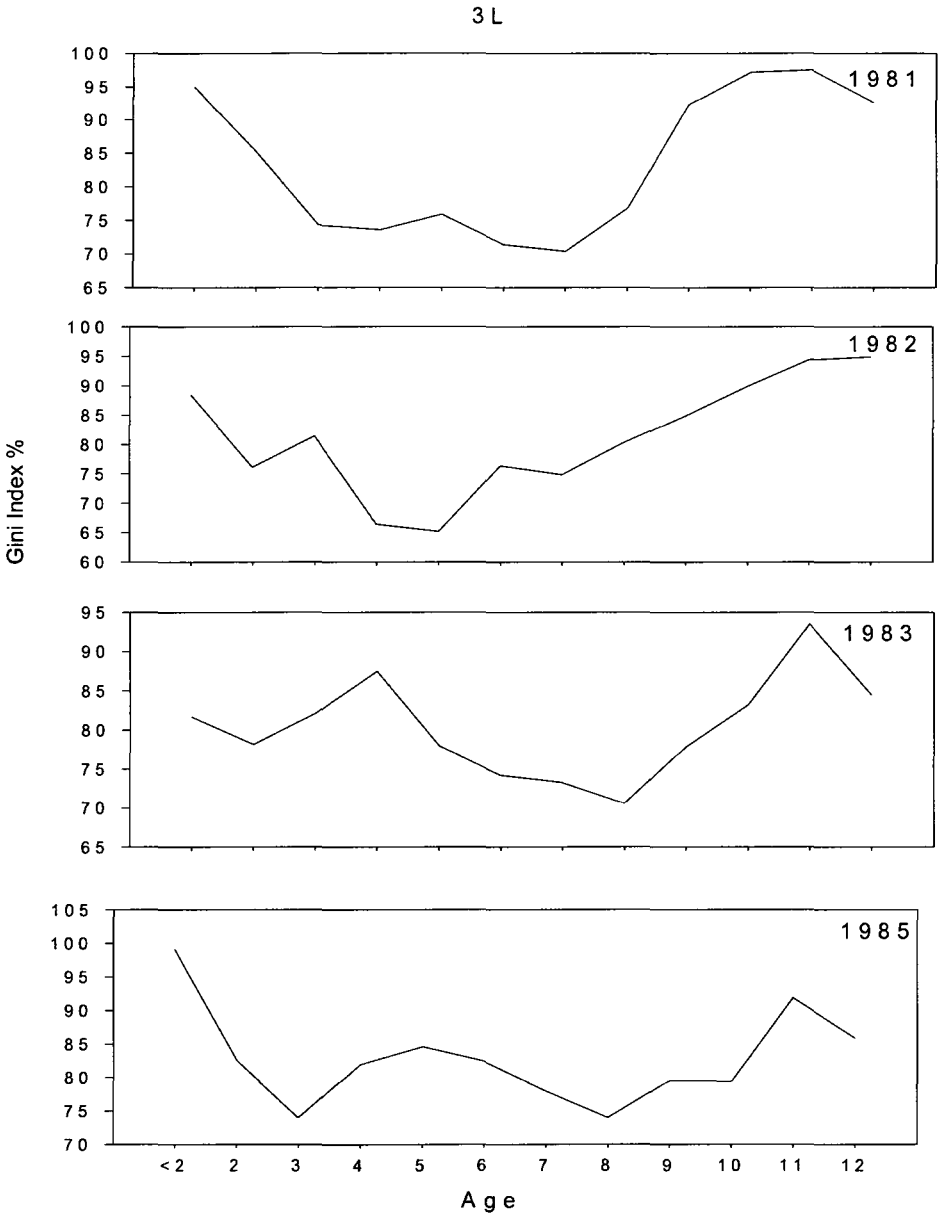

1990
1991
1992
1993
100
90
80
70
60
Gini Index %
< 2
2
3
4
5
6
7
8
9
10
11
12
Age

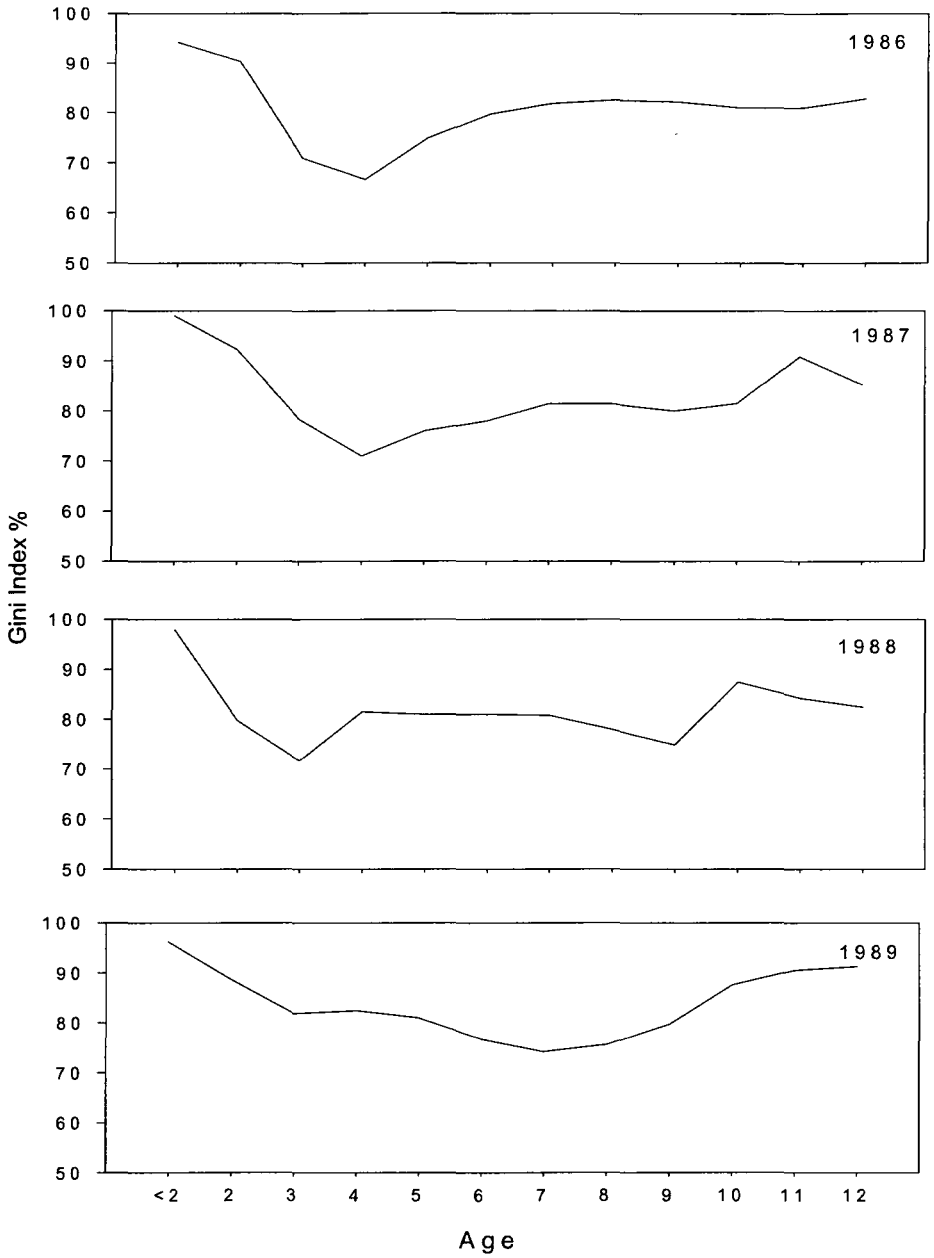

3K
1978
1979
1980
1981
Gini Index %
100
90
80
70
60
50
<2
2
3
4
5
6
7
8
9
10
11
12
Age

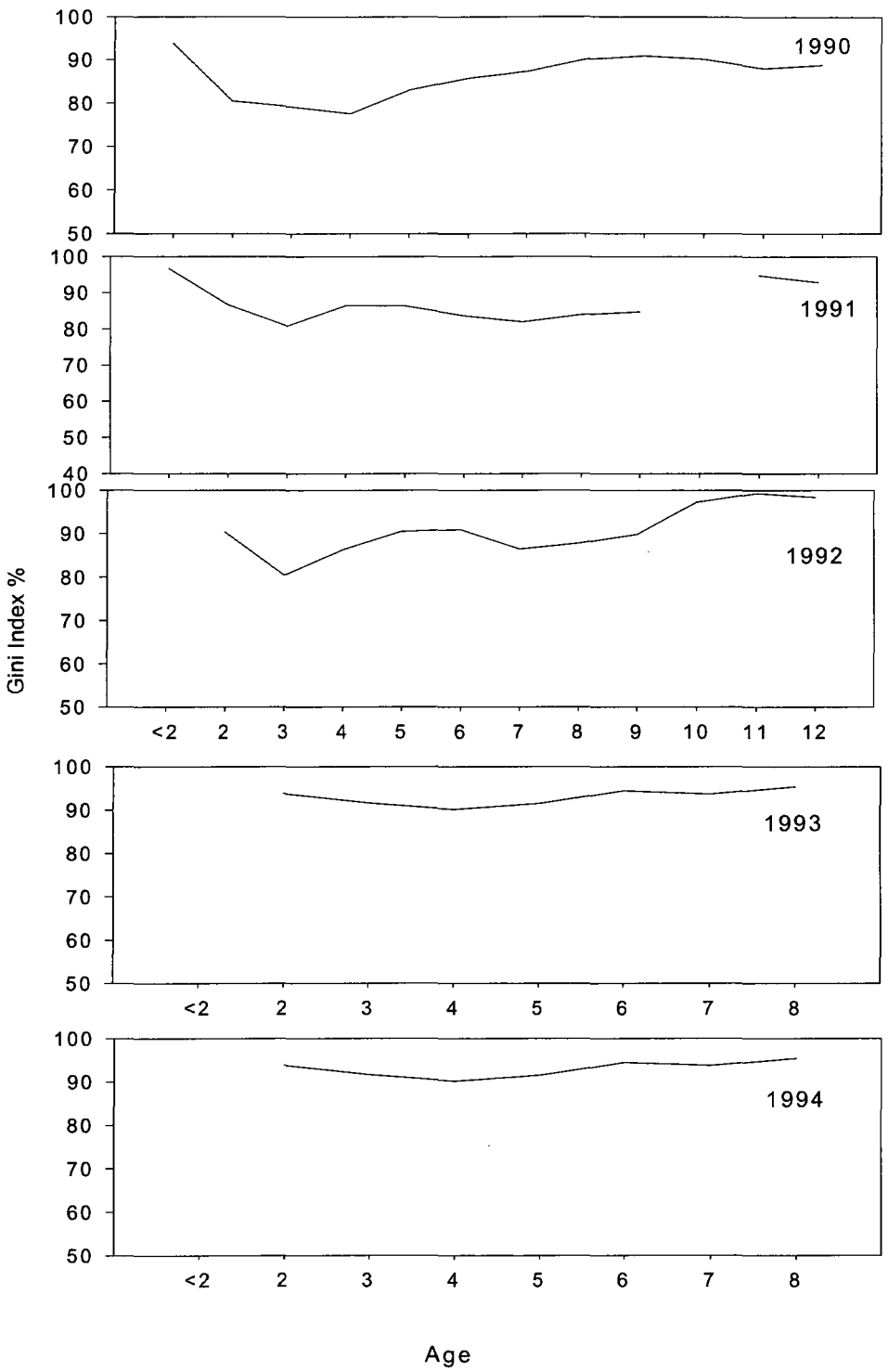

100
90
80
70
60
50
1982
1983
1985
Gini Index %
<2
2
3
4
5
6
7
8
9
10
11
12
Age


Gini Index %
100
90
80
70
60
50
1986
1987
1988
1989
<2
2
3
4
5
6
7
8
9
10
11
12
Age

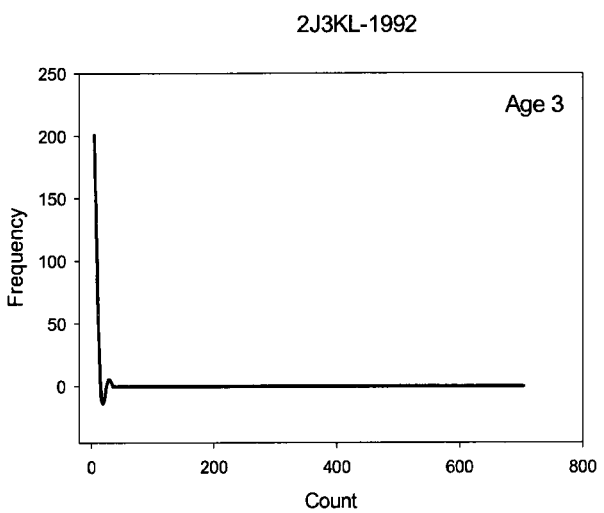

Gini Index %
100
90
80
70
60
50
1990
1991
1992
1993
1994
< 2
2
3
4
5
6
7
8
9
10
11
12
Age

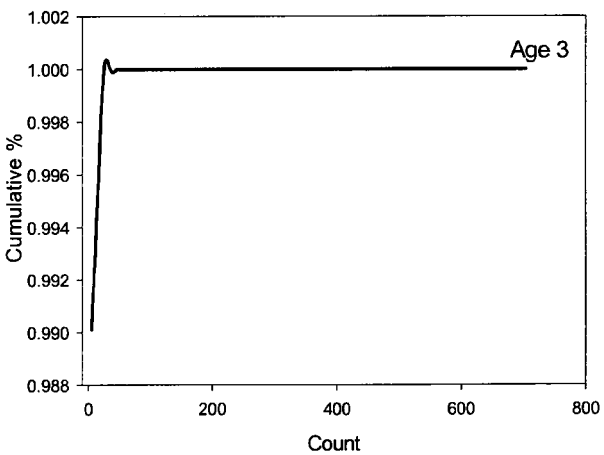

3L
1981
1982
1983
1985
Gini Index %
Age
< 2
2
3
4
5
6
7
8
9
10
11
12

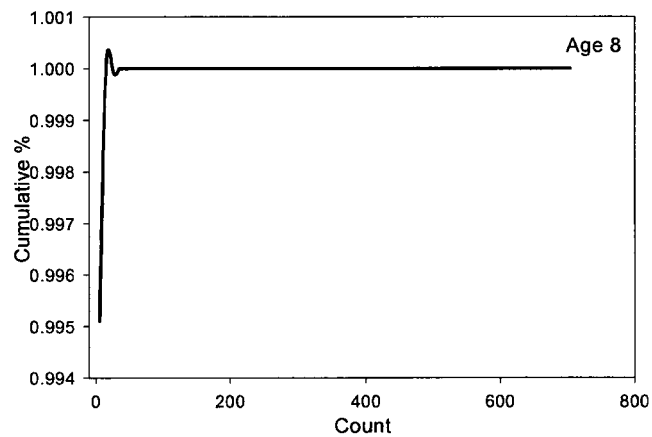

1986
1987
1988
1989
100
90
80
70
60
50
Gini Index %
<2
2
3
4
5
6
7
8
9
10
11
12
Age

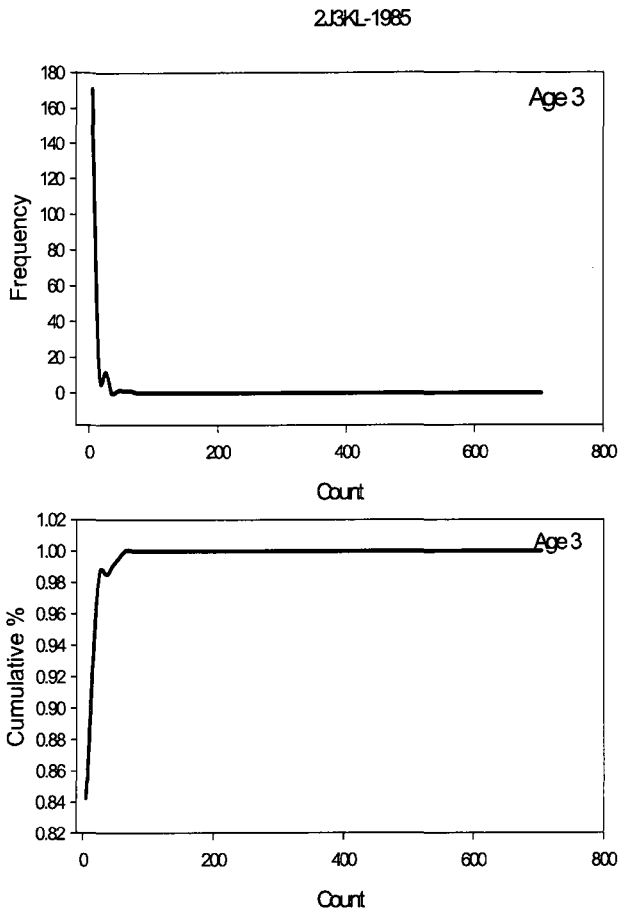

1990
1991
1992
1993
1994
Gini Index %
Age
<2
2
3
4
5
6
7
8
9
10
11
12

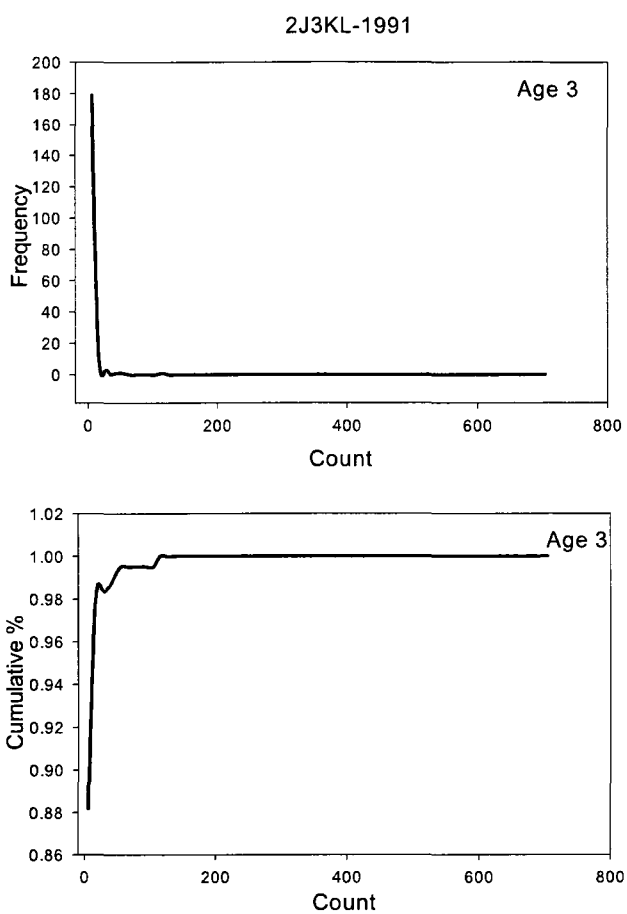
Appendix B: Samples of Cumulative Frequency Distributions and Frequency Distributions for 2J3KL and 4RS.

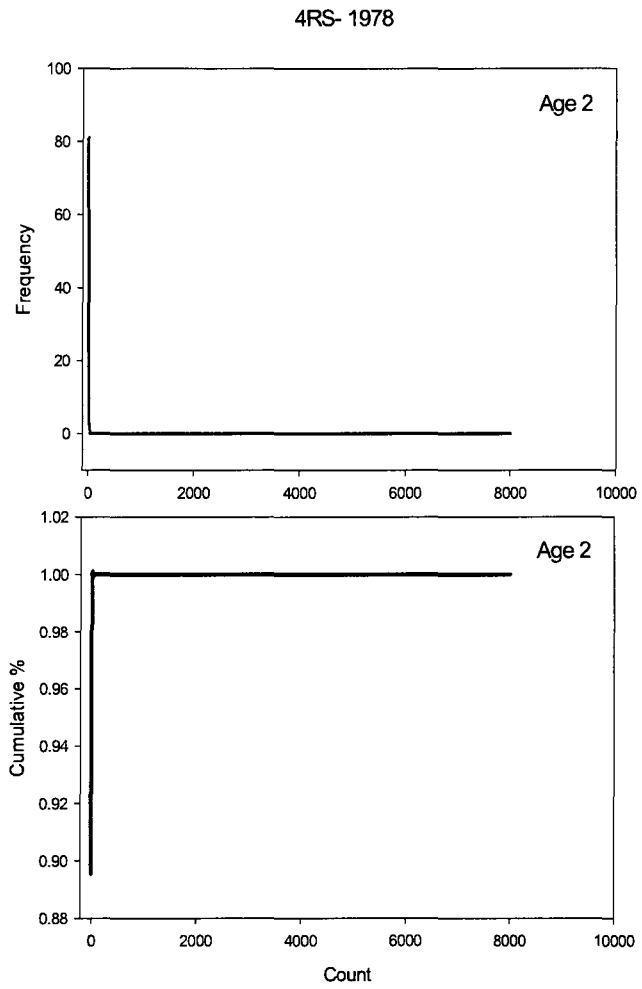


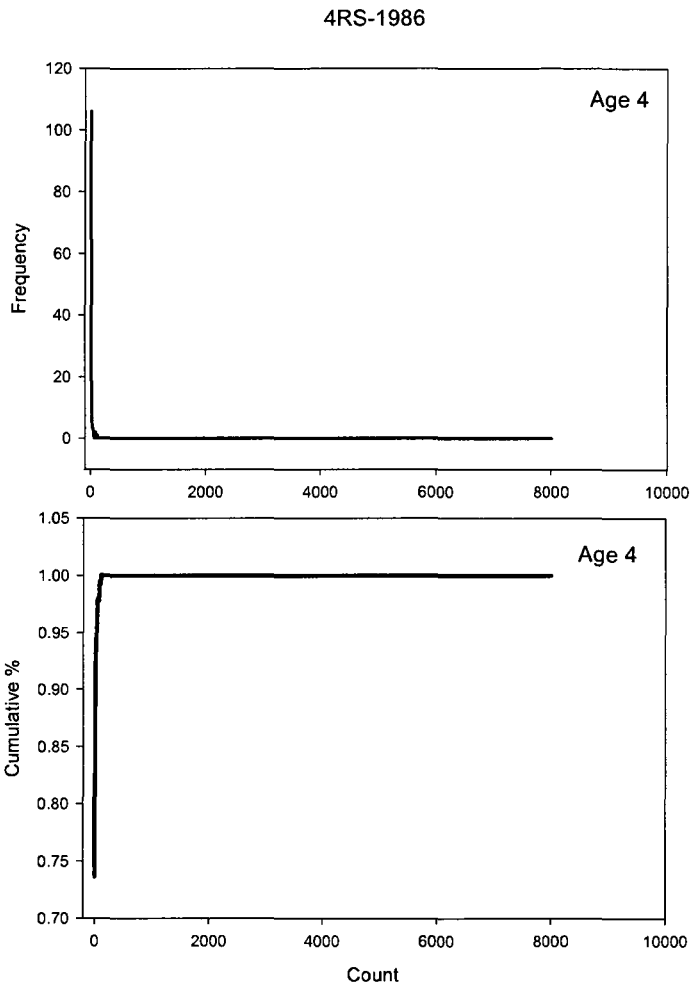





2J3KL-1985
Age 3
Frequency
Count
Cumulative %
Age 3
Count


2J3KL-1991
Age 3
Frequency
Count
Cumulative %
Age 3
Count


4RS- 1978
Age 2
Frequency
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
Age 2
Cumulative %
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
Count


4RS-1986
Age 4
Frequency
120
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
Age 4
Cumulative %
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
Count